S. VAVILOV

The EYE and the SUN

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THE EYE
and
THE SUN

ABOUT LIGHT, VISION
AND THE SUN

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INTRODUCTION

Wär nicht das Auge sonnenhaft
Wie könnten wir das Licht erblicken?
(Were the eye not like unto the sun
How could we see the light?)

GOETHE

Comparisons of the eye and the Sun date back as far as mankind itself. The source of such comparisons is not science. In our days also, alongside the world of phenomena discovered and explained by modern science, there continues to exist the world of conceptions of children and savages, as well as that of poets, which, intentionally or unintentionally, imitates it. This world is worth looking into sometimes, as one of the possible sources of scientific hypotheses. It is wonderful and story-like; in this world the gaps between individual natural phenomena are bridged over with links that science sometimes does not yet suspect to exist. In some few cases these links are guessed correctly, sometimes they are utterly wrong and simply absurd, but they always deserve attention, because such blunders often help to arrive at the truth. This is why it will be revelatory to approach the question of the connection between the eye and the Sun first from the standpoint of childish, primeval and poetical conceptions.

In playing at "hide-and-seek" children very often decide to hide in quite a curious way: they shut their eyes tight or cover them with their hands, and are quite confident that now nobody can see them; thus, they identify vision with light.

It is still more remarkable, however, that this instinctive confusing of vision and light remains common among adults. Photographers, men somewhat experienced in practical optics, often catch themselves closing their eyes while inserting or developing plates, when it is especially urgent to keep light from penetrating into the darkroom. If we listen carefully to our own words we shall here, too, find traces of the same fantastic optics. Without noticing it people say: "his eyes began to sparkle," "the sun peeped out," "the stars look down."

In poetry endowing the luminaries with the gift of vision, and eyes with the properties of light sources is quite the usual, one might say, obligatory practice:

The stars of night
Look down like keen accusing eyes,
And haunt him with their mocking glance.

. . . His eyes dart fire. . .

PUSHKIN

With you we gazed upon the stars,
And they on us.

FET

Rays—these attributes of the luminary, inevitable for visual perception—are likened to eyelashes:

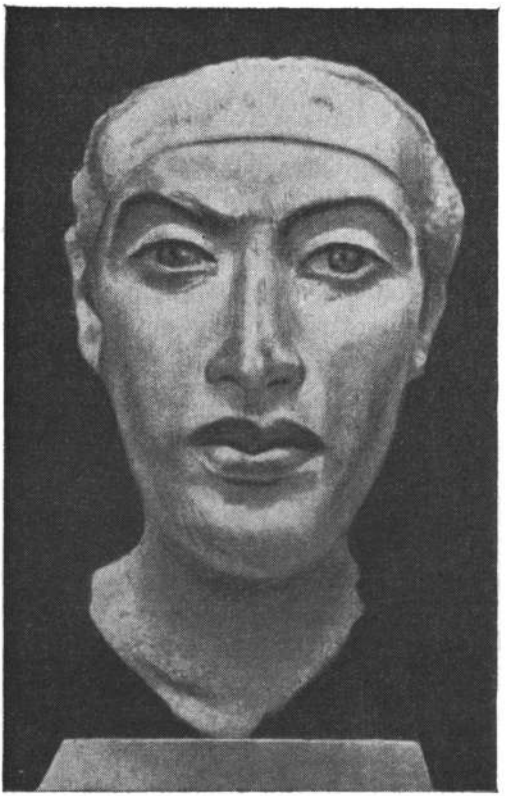
Scintillate the golden lashes of stars.

FET

Such examples can easily be found in great numbers in the works of any poet, ancient or contemporary.

In Egyptian myths, hymns and images the connection between the eye and the Sun was assumed to be inseverable and intricate.

How beautiful both eyes of Amon-Ra,



Amenophis IV, founder of the cult of the real Sun in Ancient Egypt (1370 B.C.)

says a Theban hymn, meaning by the eyes of the deity the Sun and the Moon. Other lines of the same hymn suggest a complicated interlacement of the conceptions of light and vision:

Men began to see,
When first thy right eye sparkled out,
And thy left drove off night's gloom.

The ancient religious symbol, the "all-seeing eye" had the form of an eye surrounded by rays (fig. 1). Here the eye sees and gleams at the same time. The eye and the Sun, vision and light, are fused into one image.

Such is the fundamental, though unconscious "thesis" of pre-scientific or extra-scientific optics; but there is yet another thesis.

We are constantly saying that light "cuts through," "strikes," "breaks through," "pours." The term "luminous flux," accepted in science and engineering, means, literally, a flow or stream of light. In poetry, likening light to a fluid is quite an inevitable turn:

The gold of his rays to the Pharaohs' nostrils
streams.
May I be shower'd daily with thy beams.

EGYPTIAN HYMN

Again with greedy eyes do I
Drink in the vitalizing light.
... Lightning-like sprays out the beam.

TYUTCHEV

And sprays the Sun in handfuls
Its rain all over me.

YESENIN

At times this conception of light as of something corporeal assumes distinct outline. In Egyptian images of the period of Amenophis IV (1350 B.C.) the rays of the Sun's disk—Aton—(fig. 2) terminate in hands. The Russian for "ray" (lootch) means also "arrow." Sometimes a similar crude materialization of light can be observed in our instinctive movements. In his reminiscences M. Gorky relates: "I saw A. Chekhov in his garden, catching sunbeams and trying—with no success whatsoever—to get them on his head together with his hat." Catching sunbeams in one's hat is hardly less odd than the sun hands of Aton.

This persistent likening of light to a moving body or fluid in childish, primeval, and in our own instinctive images, obviously testifies to the spontaneous, subconscious materialism of these conceptions. At the same time, it is doubtless that the identification of light and vision is due to a primitive confusing of the outer world with our own sensations. This confusion, strong in children and savages, survives to some extent in adults and civilized persons, when in a state of "subconsciousness." It was primarily the clear-cut distinction of the outer world from subjective experiences that spelled the victory of materialistic science.

Consciousness, of course, inevitably comes in its time, and breaks up the delicate lattice-work of childish and poetical "optics." The child gradually begins to distinguish his sensations more and more definitely from the external world; dreams are distinctly separated from reality, illusory feelings from actual fact. Pushkin certainly knew that eyes do not "dart fire." Fet, of course, was aware of the fact that stars cannot "gaze," Chekhov did not need to be convinced that a sunbeam could not be caught.

Still, for the poet, the world of childish conceptions remains attractive to this day, remains the easiest and most picturesque way of reaching the imagination. For

this reason, in poetry and in everyday life the "optics of children and poets" will probably survive for a long time to come. It lives alongside of consciousness, of science, without meddling in them in our days, although in the past, no doubt, it had some influence even over science.

In this respect, the history of the science of light is especially instructive. It began precisely with an attempt to carry the "optics of children and poets" into the realm of conscious, progressing knowledge. The two "fundamental theses" of this optics, viz., the postulation of the identity of vision and light, and of the corporeality of light, became the basis of the science of light in Ancient Greece and survived in various forms almost up to the XVII century A. D.

Plato, for instance, in his famous "Timaeus," a dialogue on natural science, writes:

"And of the organs they (the gods—*Tr.*) first contrived the eyes *to give light*, and the principle according to which they were inserted was as follows.

"So much of fire as would not burn, but gave a gentle light, they formed into a substance akin to the light of everyday life; and the pure fire which is within us and related thereto they made to flow through the eyes in a stream smooth and dense, compressing the whole eye, and especially the centre part, so that it kept out everything of a coarser nature, and so allowed to pass only this pure element. When the light of day surrounds the stream of vision, then like falls upon like, and they coalesce, and one body is formed by natural affinity in the line of vision, wherever the light that falls from within meets with an external object. And the whole stream of vision, being similarly affected in virtue of similarity, diffuses the motions of what it touches or what touches it over the whole body, until they reach the soul causing that perception which we call sight. But when night comes on and the external and kindred fire departs, then the stream of vision is cut off; for going forth to an unlike element

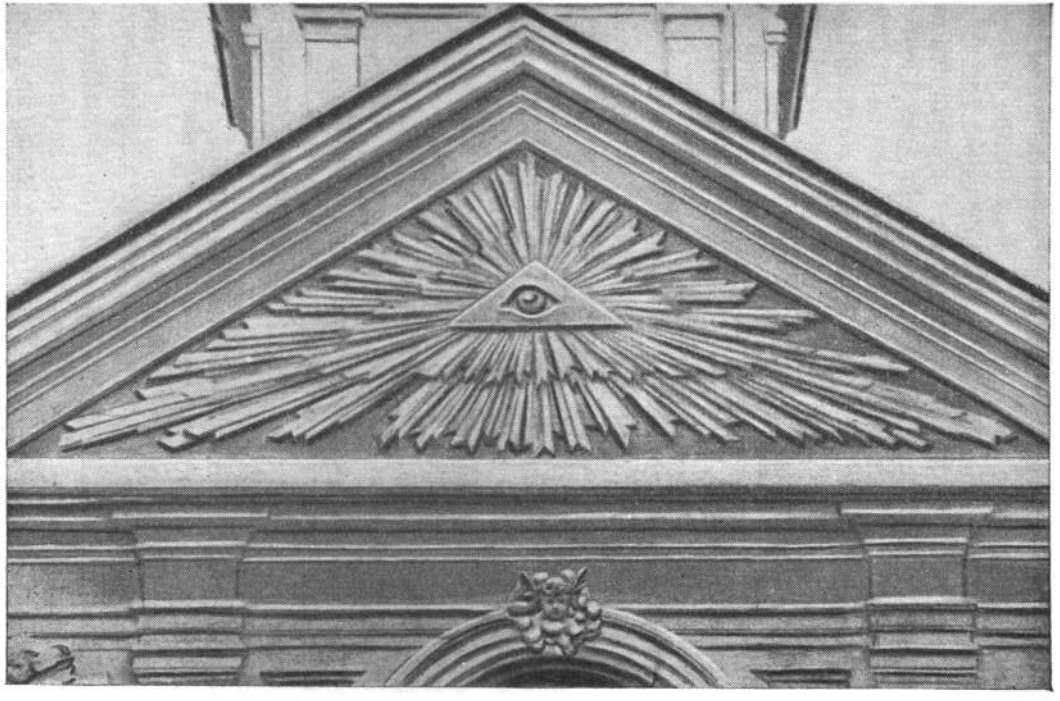


Fig. 1. Sculptural image of the "all-seeing eye" on pediment of the Lyceum Church, Town of Pushkin

it is changed and extinguished, being no longer of one nature with the surrounding atmosphere which is now deprived of fire." Thus, with Plato, the gentle fire of the eyes corresponds to the wild fire of the Sun, the closing of the eyelids for the night, to the setting of the Sun.

Damianos of Larissa (IV century A. D.) attempted in the following manner to defend the vision ray theory, according to which vision was supposed to be due to rays emitted by the eye. The shape of our eyes, which, unlike the other sensory organs, have no apertures, and are therefore not adapted to perception, but are spherical, proves, according to Damianos, that the rays are emitted by ourselves. That these rays are light rays is evident from the flashes that blaze forth from the eyes. The eyes of nocturnal animals even glow at night.

The great mathematicians of ancient times, Euclid, Ptolemy and others, on the basis of the emission theory, built up a theory of light reflection by plane and spherical mirrors, and founded the science of geometrical optics, which has retained its significance to our day.

It is natural to ask how the strikingly high, for its time, level of Grecian science in the fields of geometry, astronomy, mechanics and others, can be co-ordinated with the obviously absurd, to people of today, vision ray theory, expounded by the same Euclid and Ptolemy who left immortal works in geometry and astronomy.

Our perplexity is due to forgetfulness of historical perspective. The chief problem, and at the same time the most difficult one, confronting the ancient opticians, was how to explain the *images* of objects. In those times images were known only from the very process of vision, or from drawings and paintings. There were no other methods; not even the simple camera obscura was known, nor did anybody suspect it possible to obtain images of objects on surfaces of all kinds by using lenses and concave mirrors. Besides, the ancients were unfamiliar with the structure of the eye: they knew nothing of the forma-

Fig. 2. Egyptian image of real Sun worship from el-Amarna. Period of Amenophis IV

tion of images on the retina by means of the crystalline lens in the eye.

Under such circumstances, vision, the formation of images in man's brain of the objects surrounding him, was a very puzzling phenomenon. The conception of vision rays acting as kinds of feelers seemed to the ancients the simplest solution to this puzzle.

Imagining ourselves in the place of the ancient optician, let us consider the problem of how the image of the luminous point A in the plane mirror SS is formed (fig. 3). The ancients knew that light travels in straight lines, and they knew the law of reflection. If they had assumed, as we do now, that the light is emitted from A, then, on the basis of rectilinearity and the law of reflection they would have drawn the rays ABD and ACE. They would have found that the rays hit the eye at D and E. But the subsequent fate of these rays would have remained unknown to them, and the formation of the image in the mirror at A' could not have been understood, the more so, since, as the drawing shows, the rays, in approaching the eye, do not converge, but diverge. In coping with this seemingly unsurmountable difficulty, there came to the ancient's aid the vision ray conception, derived from the primitive images of the child and the savage. Indeed, let us assume that the rays which create the image do not travel from the source to the eye, but the other way around, and that the eye somehow senses the *original* direction of the vision rays it emits. Then, in our example of reflection from a plane mirror (see fig. 3), these rays are reflected from the mirror, like the light rays, at C and B and converge in the "source" at A. Assuming as the ancients did, that the original direction of the rays emitted by the eye is "signalled," in some manner to the brain, we find, however, that they seem to meet at the imaginary point A', where their projections intersect. The advantage of this explanation is that there is no need to know what happens to the light inside the eye. It is sufficient to as-

sume, as has been mentioned, that the original direction of the rays is signalled through the eye in some manner. The unreal image is produced in the brain. Notwithstanding the fancifulness of the vision ray conception, it was doubtlessly useful and progressive for its time, since it permitted the development of a correct theory of the production of images by mirrors. That is the reason it survived for so long a time. As late as the beginning of the XVII century, Galileo sometimes resorted to this theory.

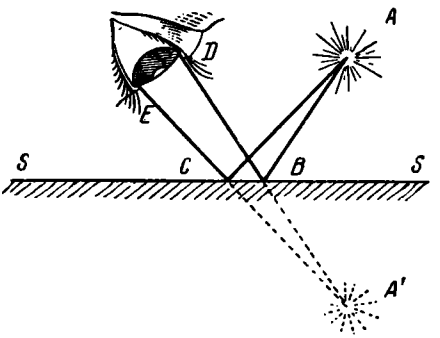


Fig. 3. Observation of the reflection of a luminous point in a mirror

In ancient times the vision ray theory was opposed only by the even more fantastic conception of Epicurus and Lucretius, which involved "thin filmy images" of objects flowing continually in all directions and hitting the eye. According to Epicurus, luminous and illuminated bodies are continually giving off very thin films, which exactly copy the relief and peculiarities of the body they come from. According to the ancient atomists, these fully developed prints hitting the eye, account for the visual image produced. This idea "saved the situation," so to say, but was entirely qualitative, and, of course, Euclid and Ptolemy's quantitative geometrical optics must be considered more perfect.

We have dwelt quite at length upon the vision ray theory in order to show that this was no gross blunder on the part of the ancient opticians, but a sort of least of evils.

For many centuries, from generation to generation, it was taught that the Sun and the eye were brothers, manifestations of the same material fire, now wild, now gentle; that to emit light meant to see, and to see—to emit light. The Earth was considered the centre of the universe, and man—the centre of this centre. The dividing line between poetical imagination and science was in many cases indistinct, faded or simply non-existent. Poetical fantasy was carried into science in an attempt to unite the two. This unity, however, was never stable.

But sometimes it was the other way around: consciousness and rudiments of objective science would find their way into the realm of myths and religion. The religion of ancient Egypt was one of Sun worship. The incommensurability of the Sun and the Earth, of light and the eye, appeared in this religion as the relation between God and man. This God was conceived now as a falcon, now as a man with the head of a falcon, and with the Sun's disk, sailing over the heavens (fig. 4):

Amon-Ra, the falcon deity,
With his scintillating feathers,
Spanning the heavens with one flap of his wings—

such is the image of the Sun in an ancient Theban hymn.

But in the XIV century B.C. the world outlook of the Egyptians underwent a significant change. It is natural to believe that the new trend was primarily a result of the observations and thought of Egyptian astronomers. History, however, has failed to retain their names. The official stone hieroglyphs, of course, connect the revolution in the Egyptian ideas of the Sun with the Pharaoh. And so, Pharaoh Amenophis IV became the Egyptian Cop-

ernicus. During his reign a new religious cult is introduced, involving worship of a real, genuine Sun, no falcon, or scarab, but the visible solar disk with its rays. The Pharaoh changes his name (Amenophis means "the beloved of Amon"), taking the name of Ikhnaton—the favoured of Aton, the solar disk. On monuments (see fig. 2) the deity is rendered simply as a disk with rays. Light

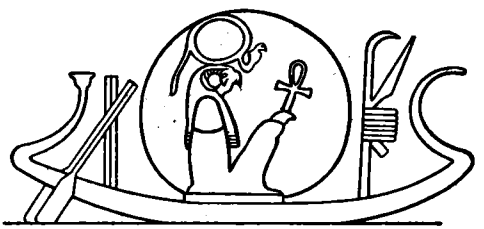


Fig. 4. Egyptian depiction of the Sun as a deity in a boat

and life are the only manifestations of the new deity. In the hymns to Aton we no longer find the diversity, the splendour, nor the intricacy of the symbols for the Sun, as of old; now it is the beneficent action of the Sun on man and on all living things that is sung:

Beautifully dost thou glow up in the sky,
Thou, Aton, who livest and hast lived eternally,
When thou risest up in the East,
Thou fillest with thy beauty all the lands.
Luminous art thou, grand and brilliant, and thou
Risest high above the lands.
Thy rays embrace the lands
And all thou hast on them created—

so, simply and comprehensibly, begins a long hymn to the Sun. The significance of the Sun for the Earth had

become distinct and real, and, it would seem, equality of the eye and the Sun was now entirely out of the question. But the cult of the real Sun disappeared in Egypt together with Ikhnaton, and thousands of years had to pass before there came a science free from the arbitrariness of human sensations and instincts, a science in which man completely rejected the idea of the privileged status in the universe ascribed to him by religion and ancient science. Man came to regard himself as one of the phenomena of nature, as a product of the age-long development of the living world on Earth.

However, the ancient conjecture as to the affinity of the eye and the Sun has remained in modern natural science, though in a profoundly altered form. In our days science has discovered the true connection between the eye and the Sun, a connection entirely different from that inferred by children, poets and the ancients. It is this true connection that the pages to follow are about.

But apart from science, and side by side with it, poets, and all the rest of us, will still be talking for a long time to come, about shining eyes and gazing stars, just as four centuries after Copernicus we still keep saying that the Sun rises and sets.

LIGHT

> To what end have so many great men devoted their labour and exposed themselves to danger and suffering? Is it only for the sake of looking and wondering at great numbers of different things and substances massed together in a confused heap, without thinking about their proper arrangement?
>
> LOMONOSOV

About 150 million kilometres lie between the Earth and the Sun; to cover this distance would be the same as to travel 4000 times around the Earth. What, then, is this light that keeps continuously bringing the eye news of the Sun from such a long way off, and, primarily, how is light to be distinguished from the other things around us; what are its characteristic features? Up to the XVII century the answer to these questions was as follows: light is what the eye sees, the cause of visual sensations. This property of light is obviously unsatisfactory as a distinguishing feature. Press your finger lightly against your eyeball near the arch of your nose in utter darkness, and you will see fantastic bright spots. If we called the cause of this visual sensation light, we should have to return to the "vision ray" conception mentioned in the Introduction. Not every cause of visual sensations can be called light. On the other hand, one might ask, is every kind of light visible? Doubtless, it is not. As we shall soon see, there is an infinite diversity of invisible phenomena which we shall have to call light phenomena.

Thus, in the very beginning of our study of light we have come up against a serious difficulty: we do not even know as yet what the subject of our study is. To get out of this blind alley let us make a closer inspection of our visual impressions.

Visual images have two fundamental properties—*brightness* and *hue*—properties which are obvious to all who can see, and which require no further explanation.* But both brightness and hue are quite relative and subjective. In the day-time the Moon cannot be distinguished from the clouds; at night it is promoted to the rank of the Sun's deputy, the "second eye of Amon-Ra." The stars, invisible during the day, seem exceedingly bright against the background of a Moonless night sky in autumn.

The second feature of visual sensations—hue—is no less deceiving. We distinguish black, white and the intermediate shades of grey. All kinds of coloured hues, such as those that make up the rainbow, seem to us essentially different from black and white. Actually, the difference is to a considerable extent subjective and relative. This can be proved by performing the following simple experiment. One half of a white cardboard disk, fixed on a wooden pin to form a top, is blackened by gluing on a half-circle of black velvet or by coating it with a good-quality dead-black paint. Concentric black arc-shaped bands are painted or glued on the other half of the disk, as shown in fig. 5 (Benham's top). If this top is illuminated brightly with a white light, such as sunlight, and set spinning, we shall observe at a certain speed, not the

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* Closer observation discloses a third property, called *saturation.* For instance, we see two equally bright surfaces next to each other, both of them red, but we say that the colour of one of them is purer, more saturated, while that of the other is of a lighter tint, as if diluted with white. This admixture of "white" serves as a measure of unsaturation.

grey concentric circular bands we expect, but coloured ones instead, though rather dark and of low saturation. Thus, blending black and white under certain conditions gives rise to coloured images.

This leads us to the disconcerting conclusion that in defining light it is not enough to proceed solely from visual sensations. That is why the only thing in the science of light that was quite clear for a period of over two thousand years after this science was founded, were the geometrical properties of light rays. All the rest, based on subjective visual impressions, remained unexplained, blurred and indefinite for hundreds and thousands of years.

Fig. 5. Benham's top

Optics was brought out of this deadlock only in the XVII century, by Isaac Newton, who at last succeeded in translating the subjective sensations of brightness and hue into the objective language of measure, number and physical relationship. In 1665 Newton began his experiments on sunlight. In these experiments a beam of sunlight, admitted through a round hole in the window shutter, fell on a glass prism. The beam was refracted by the prism, and thrown on to a screen, where it gave an elongated image with the same sequence of colours as in the rainbow. The appearance of such a rainbow (spectrum) when light is passed through a prism had been observed long before Newton, and was attributed to the fact that glass acts on white light in some way, changing its colour. Newton concluded from his experiments that this was not so. White light (according to Newton) is a complex mechanical mixture of an infinite diversity of rays, which are refracted by the glass to various degrees. The prism does not change the white light, but resolves it

into its *simple* constituent parts, which, if blended, will again produce the original white colour (fig. 6). If a pure, for instance red, ray is separated out of the rainbow-coloured fan produced by the prism, and passed through a second prism, no further change will occur; hence, the first resolution effected has resulted in something constant. The chromaticity of this constant, simple colour, however, does not by itself reveal the nature of light; it remains subjective and relative, as before. If, for instance, we blend simple red with green, we get yellow, a colour similar to one of the pure rays of the solar spectrum; if we blend green and violet, we get blue, etc. The eye in these cases is unable to distinguish the mixed colours from the simple ones; this can be done only with the help of a prism or, in general, a spectral instrument which will resolve the light *spatially* into its simple colours.

It was this *spatial arrangement* of the simple colours, and not their different chromaticity, that gave Newton the clue to the first objective and quantitative feature of light corresponding to its subjective chromaticity. Newton showed that the spatial arrangement of the simple colours is due to their different refrangibility by the prism. Refrangibility can be expressed by a definite number, the index of refraction. Thus, Newton finally succeeded in leading the science of light out of the indefiniteness and confusion of subjective impressions on to the straight and stable road of mathematics.

After Newton, further study of the refraction of light by various bodies showed that refraction depends greatly on the substance of the prism. In ordinary glass and quartz prisms blue rays are refracted more than red, just as in the rainbow; but with very thin prisms made of solid dyes (such as fuchsine, for instance) spectra of quite an unusual kind can be obtained, in which the red rays are refracted more than the blue. Thus, the index of refraction turned out to be a complex property, de-

pending not only on the kind of light, but on the kind of substance as well.

Newton, however, discovered another striking property of pure rays, which made it possible to define them

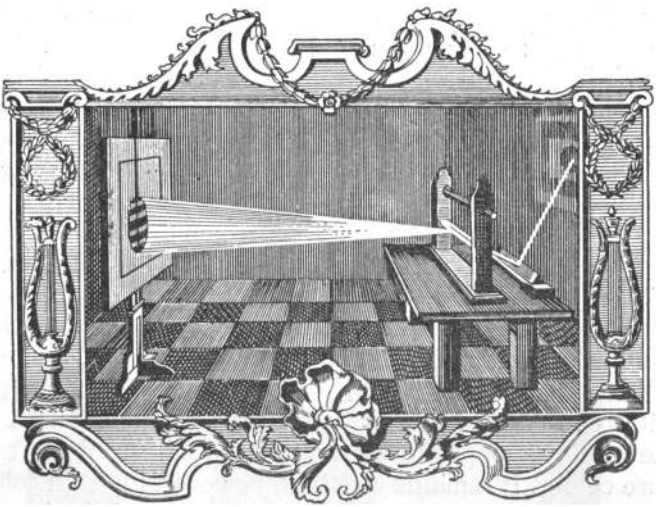

Fig. 6. Apparatus for prismatic resolution of solar light in a dark room, set up in the Kunstkamera (Chamber of Arts) of the Petersburg Academy of Science in the first half of the XVIII century. (From drawing by Academician Kraft.)

quantitatively, quite irrespective of the nature of the substance. If a slightly convex eye-glass is placed upon a flat glass and illuminated with white light, a number of concentric iridescent rings will appear around the point where the glasses touch. Instead of white light Newton tried illuminating the glasses with pure rays procured by passing sunlight through a prism. This disclosed an even more wonderful phenomenon. If they are illuminated,

say, with red rays, a large number of regular, concentric, alternating red and black rings appear around the point of contact (fig. 7). The further out from the central dark spot, the smaller the distance between the rings. Newton found that the radii of the dark rings are to each other as the square roots of the consecutive even whole numbers, i.e., as $\sqrt{2} : \sqrt{4} : \sqrt{6} : \sqrt{8}$.

If the flat glass is removed, and the lens placed upon a non-reflecting surface, the rings disappear. Hence, Newton found that the rings appear only if a lens and a flat glass with a very thin layer of air between them (fig. 8) are used. It is not difficult to prove geometrically that the thickness of the air layer corresponding to each successive light and dark ring increases as the consecutive whole numbers. The thicknesses of the layers opposite each ring are multiples of that opposite the first and smallest. Illuminating the glasses with various simple colours changes the width of the rings. They are widest with red rays and narrowest with violet. The thickness of the air layer opposite the first ring is different for each pure colour. It remains constant, however, for each colour irrespective of the convexity or substance of the lens. It varies only if the air is replaced by some liquid. In this case the width of the rings depends on the index of refraction of the liquid.

The results of these simple experiments with lenses, which were first performed by Newton and are easy to repeat (they are even simpler than the experiments with the prism), are quite remarkable. Indeed, they reveal, first of all, a kind of regular *periodicity* in the luminous flux. Secondly (and this is no less striking), although the entire surface of the lens is uniformly illuminated by the incident rays, the reflected or transmitted light shows dark, i.e., unilluminated rings.

We shall return to these phenomena presently and explain them. Just now it is important to establish that on the basis of the Newtonian ring experiment each simple

Isaac Newton (1642—1727)
(From life drawing by Steclay)

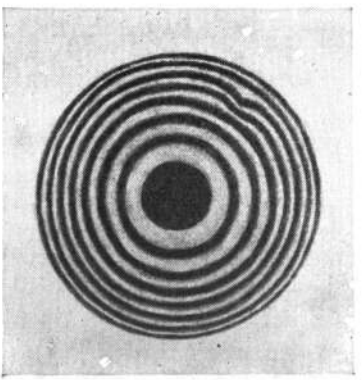

Fig. 7 Newtonian rings

colour can be connected with a definite thickness of the air layer between the glasses, corresponding to the first dark ring. Hence, a pure colour can be defined quantitatively by the thickness of this first layer (see fig. 8), instead of the index of refraction. For the time being, we shall conventionally call this thickness the wave-length

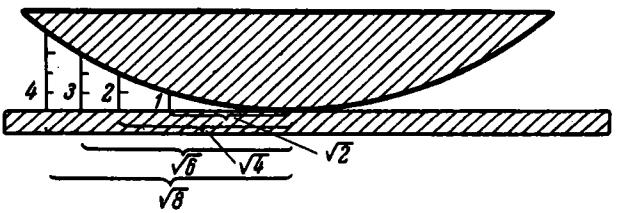

Fig. 8. Origin of Newtonian rings

and denote it by the Greek letter λ. The wave-lengths of visible light, as Newton first showed, are very small and are usually expressed in special units called millimicrons (m μ); a millimicron is equal to one-millionth of a millimetre. Newton, for instance, found that the colour on the border-line between the green and blue regions of the solar spectrum has a wave-length of λ=492 m μ. The red limit of the spectrum has a wave-length of about 700mμ and the violet limit—400mμ.

The profound significance of Newton's experiments is worth pondering over. The fanciful, subjective realm of colour phenomena, which for thousands of years had evaded all attempts of scientists to put it in order, had suddenly revealed its quantitative essence and become subject to precise scientific analysis.

In 1675, while Newton was still working on his prismatic colours and rings, Römer, an astronomer, determined the *velocity of light* for the first time, and found it to be approximately equal to 186,000 miles (300,000 km.)

per second (taking into account later corrections). Light takes about 8 min. to cover the distance from the Sun to the Earth. On the basis of the vision ray conception, according to which light travels from the eye to the luminary, the ancient opticians concluded that the velocity of light must be exceedingly high. No matter how quickly we open our eyes, we see even the most distant star immediately. Three hundred thousand kilometres per second is a snail's pace compared to the imaginary velocity of the rays emitted by the eye. If the velocity of these streams equalled that of light we could see the Sun only 8 minutes after opening our eyes.

After Römer the velocity of light was measured many times by various methods, both astronomical and terrestrial. Today this magnitude is known very accurately. For space devoid of substance it is equal to 299,776 kilometres per second. The first five digits of this figure are absolutely certain, and only the last, the sixth, is known but approximately. It is important to note that the velocity of light in a void does not depend on the wavelength; it is the same for red rays as for blue. This is proved with very great precision by the fact that eclipses of distant stars, for instance, when one of a pair of binary stars passes into the shadow of the other, do not result in any perceptible change whatsoever in the colour of the star. If the velocity of the various simple colours differed even very slightly such eclipses would inevitably lead to sharp changes in the colour of the star.

On the other hand, when light travels through substance, for instance, water or glass, its velocity depends on the wave-length, this being the reason why a spectrum appears when light passes through a prism. The occurrence of rainbows in the sky is convincing proof of the fact that the velocities of rays of different chromaticity in waterdrops are different. These velocities can be determined by dividing the velocity of light in a void by the index of

refraction. The latter is the ratio of the velocity of light in a void to the velocity of light of a given chromaticity when passing through substance.

If we divide the velocity of light by the wave-length, we get the number of changes taking place in the light-ray per second, i.e., what is called the *frequency of light.* Let the frequency be ν, the velocity of light c, and the wave-length λ. Then,

$$\nu = \frac{c}{\lambda}$$

The frequency of visible light is enormous; for instance, yellow light, with a wave-length of 600mμ, has a frequency of half a million billion cycles per second!

Now we come to a very important fact. As we have seen, the velocity of light is inversely proportional to the index of refraction of the medium. On the other hand, the wave-length λ, as we mentioned in describing Newton's experiments, also depends on the medium through which the light is passing. The Newtonian rings contract if the air between the glasses is replaced by water. The wave-length, like the velocity, is inversely proportional to the refraction index of the medium. Hence, the quotient of the velocity divided by the wave-length of light, i.e., the frequency, as may be seen from the above formula, does not depend on the substance. Therefore, this magnitude is a very important quantitative characteristic of light itself, namely, the very property that corresponds to chromaticity.

However, the velocity and the frequency of light do not define it exhaustively. From subjective impressions we know that the brightness of light may vary widely. Compare the twinkle of the fire-fly with the direct glare of the Sun, and it will immediately become clear how infinitely brightnesses may differ.

What is the physical sense of the *brightness* of light? Science was able to answer this question correctly only after the conception of energy became clear. There is no doubt that light always bears energy, which is evident from the various actions of light: heating, chemical change, etc.; in general, we recognize light only through its action, i.e., as a result of the fact that it bears energy. The sensation of brightness is closely connected with the energy of light rays. The greater the energy borne by a simple "monochromatic" (single-coloured) ray, the greater its brightness.

The eye, however, is a poor judge of luminous energy. At night even the glow of the fire-fly seems blinding, while in the day-time the eye can stand the direct light of the Sun. On the other hand, if we compare rays of different colours, we find that a red ray, for instance, seems less bright than a green one of considerably less energy. Hence, though the energy and the brightness of light are interrelated, they are entirely different conceptions. Owing to this indefiniteness, the modern optician employs objective physical methods in measuring luminous energy.

At this point we can draw a few conclusions. Now that we are free from the arbitrariness and complexity of subjective light sensations, we can affirm, on the basis of the experiments and measurements described above, that light is a bearer of energy which travels through interstellar space with a velocity of about 186,000 miles per second and possesses periodic properties. We shall try to regard everything that comes under this definition as light, irrespective of whether it causes visual impressions or not. Afterwards we shall see that this definition will have to be somewhat supplemented and modified, but for the time being it will suffice.

Indeed, since the beginning of the XIX century physicists have had to include in the field of optics wider and wider ranges of "invisible rays," which fairly overwhelm

the visible region of the spectrum. Both ends of the Newtonian solar spectrum, the red and the violet, pass into darkness. Does this blackness conceal anything? The eye sees practically nothing.

In 1800 Herschel performed a very simple experiment. He placed a thermometer with a blackened bulb in the dark region following the red end of the solar spectrum, and found that the temperature rose quite perceptibly. This meant that there were rays in this region, invisible to the eye, but capable of raising the temperature of bodies. These rays were called *infra-red*; their wave-lengths have been measured, and it has been shown that they travel with the usual velocity of light. Therefore, they come under the physical definition of light in every respect. The range of infra-red rays extends very far. In our days rays of this type have been observed with wave-lengths of about 0.3mm. Hence their range extends from the red limit of the visible spectrum, i.e., 750 mμ, up to 300,000 mμ (at least). But this is not the end of the spectrum. The electrical waves emitted by radio broadcasting stations are also propagated with a velocity of 186,000 miles per second and possess periodic properties: hence, they should also be classed as light-waves. Artificial electrical waves of this kind can be produced in a wide range of wave-lengths, from scores of kilometres to fractions of a millimetre.

Thus, from the red limit of the spectrum waves can be traced as far as the practically infinitely long waves used in wireless. But what about the other side, the region following the violet limit? The temperature does not rise perceptibly in this region, at least when usual light sources are used, but a photographic plate placed there will darken upon developing. This is how the invisible *ultra-violet* rays are revealed. There are also other ways of disclosing them. Under the action of these waves many bodies begin to emit visible light (luminescence) or electrons (photoelectricity), or become electrically conductive.

The ultra-violet range is usually considered to begin from the violet limit of the visible spectrum (which is rather indefinite, by the way—about 400m μ) and to extend far into the short-wave zone, at least down to 10m μ. Nor is this the end of the spectrum; after the ultra-violet come the rays discovered at the end of last century by Röntgen, which possess, as we know now, all the properties of light rays. Like ultra-violet rays they darken photographic plates, cause visible luminescence and electrical action. Röntgen rays (or X-rays) include (in accordance with the practical methods of obtaining them) rays approximately from 10 to 0.1m μ. This, however, is still not the end of the spectrum. After X-rays come rays with still shorter wave-lengths, the so-called gamma-rays emitted by radium and other radio-active substances. There are no grounds to draw any border-line for gamma-rays. Such rays are known with wave-lengths of less than 0.001 m μ.

It may be said that there are light rays with wave-lengths of all kinds, from infinitely large (practically) to infinitesimally small (also practically). The insignificant range of visible rays (from 400 to 700 mμ) is lost in this diversity.

Light possesses some other remarkable properties, which we have not discussed yet. Perform the following experiment (fig. 9,*a*). Pour some slightly turbid water (made turbid, for instance, by adding a drop of milk) into a glass vessel and pass a ray of direct solar light through it. The trace of the light beam will be clearly visible as a result of dispersion of the light by the suspended particles. At first sight it seems self-evident that the light should be scattered alike in all directions, irrespective of whether we observe the trace from above or through the side of the vessel. If a direct (ordinary) sunbeam is used, this will, indeed, be so.

Now perform a second experiment (fig. 9,*b*). Let the direct ray fall first upon a glass plate at an angle of

about 54° (the ray is perpendicular to the plane of the drawing), and thence be reflected into the vessel of turbid water. If the trace of the light beam is observed attentively from all sides, a striking phenomenon will be noted: observed through the side wall, the light will appear greatly scattered (a comparatively bright band of light will be seen), whereas from above there will be almost no dispersion; the trace of the beam in the water will be invisible. After reflection from the mirror the light

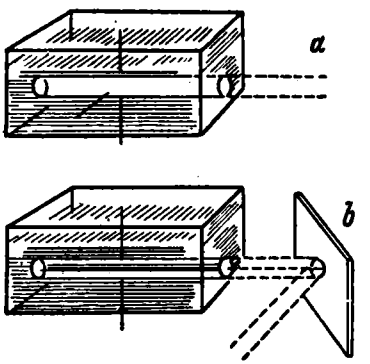

Fig. 9. Polarization of light upon reflection

has attained a new, very strange property: it no longer acts up and down, but only sideways. Preferential directions of action appear in the cross-section of the beam; it acquires *polarity*. Just as a bar magnet is most active along the line connecting its two poles, and almost entirely inactive in the direction perpendicular to this line, so with light in this case, the action is concentrated in the horizontal plane. Newton first called this property of light (in the more complicated case of so-called double refraction of Iceland spar) *polarization*, out of analogy with the magnet. An ordinary light beam is a mixture of

rays polarized in all directions; that is why polarization cannot be detected. When the beam is reflected by the mirror, the reflected rays are of a definite polarization, as a result of which the latter becomes perceptible. Not only visible rays are subject to polarization, but all those called light, from wireless to gamma-rays.

The eyes of most people cannot distinguish polarized light from unpolarized. But about 25-30 per cent of the human race possess this property, although they hardly ever suspect it. When observing a surface radiating polarized light such people can notice a pale lemon-yellow coloured band shaped like a slightly bent sheaf of grain in the centre of the field of vision. If the plane of polarization is turned, this band is seen to turn with it. With certain positions of the Sun in the sky the light coming from the sky is strongly polarized as a result of dispersion of the Sun's rays by the atmosphere, and then any person who possesses the capacity mentioned sees a dim yellow sheaf-like band in the sky.

In 1855 L. N. Tolstoy described this yellow polarization spot in the sky quite vividly, apparently, however, without at all suspecting the physical sense of the phenomenon, it being known at the time even to very few scientists (it was first described in 1846 by Haidinger). The following lines, from the XXXII chapter of Tolstoy's *Youth,* are a rare example of a great artist's subtle power of observation:

"...I would find myself laying my book down, and gazing through the open doorway on to the balcony at the pendent, sinuous branches of the tall birch-trees where they stood overshadowed by the coming night, and at the clear sky where if one looked at it intently enough, *misty, yellowish spots* would appear suddenly, and then disappear again."

The reader is recommended to check his eyes and try to observe the yellow polarization band in the sky. In this way at least some of our readers will find that their eyes

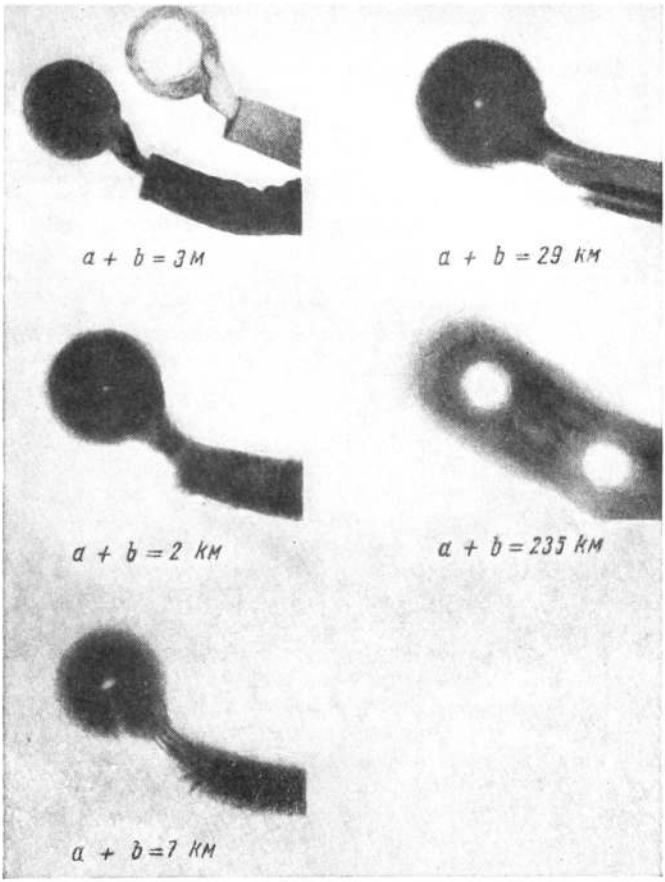

Fig. 10 Diffraction of light upon passing an opaque object (V. K. Arkadiev's experiment)

possess a property they formerly did not know of. The test is best made with light reflected from a glass with its back side painted black. At a certain angle of incidence and reflection a plate of this kind polarizes light to a considerable degree.

During recent years methods have been found of making transparent films of any size, which polarize light completely. One such "polaroid" is made on the basis of a plastic—vinyl alcohol. A thin film of vinyl alcohol, stretched in one direction, is subjected to the action of iodine vapours, after which it begins to polarize light completely. At present polaroids are widely used in laboratory practice, in engineering, in photography. If any illuminated surface, such as the sky or a wall, is observed through a polaroid, the yellow sheaf-like band will always be seen, provided the observer's eye can distinguish polarized light. If the polaroid is rotated, the band rotates with it.

We shall return shortly to the physical explanation of the polarization of light; but just now let us turn to another remarkable property of light.

Light travels through homogeneous media in straight lines, and any small obstacle put between the eye and the luminous source will hide the latter from sight. This forms the basis on which the ancients built up their orderly science of geometrical optics. But the fact itself is not always true. Look at a bright light from a distance of 20-40m. through two fingers pressed together so as to leave a very thin slit between them. Instead of a luminous point you will see an elongated band running crosswise to the slit. The band has a bright point in its centre and consists of alternating dark and light iridescent spectral stripes. This has nothing in common with the idea of light travelling in straight lines. The phenomenon described has, of course, been known to man since prehistorical times. Similar infringements of the rectilinearity of light can be observed through squinted eyes, due

to the slits formed by the eyelashes, as is especially well known to children. However, the first to point out the importance of this fact, was Grimaldi, in the XVII century.

Fig. 10 shows five photographs of shadows of a hand holding a plate, after the experiments of V. K. Arkadiev. The first photograph (at the left) was produced under the following conditions: the distance a, from the luminous point to the hand, was about 2m., and that b, from the hand to the screen—about 1m. In the second photograph $a + b$ was equivalent to 2 km., in the third, to 7 km., in the fourth, to 29 km. and in the fifth, to 235 km. While the shadow is quite distinct in the first photograph, it gradually acquires rather fantastic shapes in the rest: a distinct light spot appears in the centre of the shadow of the plate; the shadow of the arm and hand becomes lined with dark and light bands; hence, in these cases also, the idea of light travelling in straight lines is out of the question. According to the laws of geometry, rectilinear rays coming from a luminous source of small size over such a distance should yield an irreproachably regular shadow.

Therefore, when light passes through thin slits or is blocked by small objects in its path, it *bends around* them. Grimaldi called this phenomenon *diffraction.* Newton, as was his wont, studied diffraction thoroughly, and having found it to be quite independent of the substance of the slit or the object, concluded that it was therefore a fundamental property of light itself.

It was shown afterwards that diffraction is a common property of all the rays throughout the spectrum, from wireless waves to X-rays. The shorter the wavelength, the narrower must be the slits and objects to make the deviation from rectilinearity and the diffraction perceptible.

We have examined some of the most important properties of light observable by experiment: periodicity,

velocity, polarization, diffraction. Taken together, all these properties clearly suggest the general idea of light as a stream of waves with transverse vibrations. For the time being, however, let us refrain from such generalizations, until we have acquainted ourselves with all the fundamental properties of light, some of which we have not discussed yet.

Light always comes from substance, is born in substance and disappears, being absorbed by substance. Encounters between light and substance always result in interaction. On the one hand, substance reflects, refracts and absorbs light, is capable of turning its plane of polarization. The action of substance on light begins at a distance. Rays from the stars coming past the Sun at a distance of millions of kilometres deviate perceptibly from their paths, as if attracted by the Sun; as a result of this the stars seem displaced from their normal positions in the sky. On the other hand, when light strikes substance it acts on it in various ways. Light exerts pressure on substance, although the magnitude of this pressure is very small. Light may lead to chemical change in substance (photographic plates, plant leaves, sun-tan, etc.). Light may cause electrons—composite parts of atoms—to be emitted from substance. The passage of light may make substance begin to emit light itself (light dispersion, fluorescence, phosphorescence). Finally, the absorption of light by substance leads to a rise in temperature.

At the outset of the present century M. Planck made a very important discovery. He found that light can be absorbed or emitted only in quite definite units of energy, which he called quanta.

Let us consider one of the cases of the chemical action of light. A piece of paper or fabric dyed in a thin layer fades gradually under the action of sunlight. The dye consists of very minute particles—molecules, evenly distributed over the surface of the fabric. All the mole-

cules are the same, and the light that falls on each is apparently the same, and still, the fabric fades gradually, i.e., the molecules decompose one by one. If the light falls uniformly, and all the molecules are alike, it should be expected that either all the molecules will decompose at once, or none of them will decompose, or that the decomposition will occur instantaneously, eruptively, after a certain length of time, when the molecules will have absorbed a sufficient amount of energy. Actually, the process is very slow and gradual. How is this to be accounted for? It remains to assume that either the molecules are not identical, or the front of the incident light is not uniform: that the energy is concentrated in some points and absent in others. There are no grounds to doubt the identicalness of the molecules, which is borne out by chemistry practice. We come to the conclusion that the front of the apparently homogeneous light beam is, in reality, not homogeneous. Its energy is concentrated in definite centres spatially separated from one another.

In studying not only the chemical action of light, but all other kinds of light action as well, physicists came to the general conclusion that they all take place as if the particles of substance were capable of absorbing and radiating light only in whole quanta. The light quantum was given the name of *photon.*

The magnitude of a quantum of a pure light with a frequency of ν per second is $h\nu$, where h is a constant value of very small magnitude (6.62×10^{-27}, *i.e.*, 6.62 divided by a one followed by 27 zeroes). From this point of view the gradual fading of the fabric is quite comprehensible. The energy of a luminous flux is not distributed uniformly and continuously, but is concentrated in certain centres, called quanta. Only those molecules of the substance decompose, which are struck by light quanta. In some cases the following line of reasoning holds. If during a definite period of time the amount of

energy absorbed is E, the number of molecules decomposed can be found by dividing this energy by that of a *quantum*:

$$N = \frac{E}{h\nu}$$

In simple cases of chemical decomposition under the action of light this conclusion is accurately confirmed by experiment. The interrupted quantum nature of light action manifests itself in all cases: in heating substances, in the electrical action of light, in fluorescence, etc. It is especially remarkable that with very weak luminous fluxes the human eye can also perceive the interruptedness of luminous energy. We shall return to this in the last chapter of the book.

The frequency ν of wireless waves is relatively very low, therefore the quantum $h\nu$ is also exceedingly small; in this case it is very difficult to perceive the interrupted nature of the waves. On the other hand, the quanta of X-rays, which have a very high frequency, are large, and their quantum actions are especially clear-cut and distinct.

And so, we must now add one more very important property to our list of the fundamental properties of light, one difficult to associate with the previous features of light. Although we have not as yet exhausted the fundamental properties of light known at present, we shall now pass over to attempts at explaining its physical essence. This will make it somewhat easier to understand and remember phenomena.

Conjectures as to the nature of light began to spring up and be rejected a very long time ago. Many of them were absolutely groundless, dealing, as they did, essentially with things unknown: with a phenomenon, the properties of which were undiscovered. They confused vision and light, which led to strange theories such as the vision ray theory discussed in the Introduction. There

were also, however, conjectures that came quite close to the present-day theoretical views.

Light conveys energy from the Sun to the Earth through vast space. The ancients also knew, or rather sensed this.

How can energy be transmitted over great distances? The methods are not so numerous. The simplest is to transfer it from one place to another together with substance. A gun-shot is a transference of the destructive energy of gunpowder from the shooter to the target by means of the flying bullet. Energy can be transferred together with substance in a continuous flow, by an avalanche, but in essence this is the same method as the former. In both cases the substance travels together with the energy. But there is another method. A sea wave, raised by the wind, travels on and on, until it finally crashes down upon the shore, giving away its energy. But if waves are examined closely there is no difficulty in noticing that while the wave goes on the water does not go with it, but just stays in the same place, heaving up and down. Energy is transferred from layer to layer without the substance migrating. The energy of sound is transmitted through air in exactly the same manner. A sound wave is not a wind, but a consecutive vibration of air layers. "If the air," reasons Lomonosov in his *Treatise on the Origin of Light*, "travelled from the strings in a passing current as swiftly as the tune, i.e., over 1,000 feet per second, such music would tear the very mountains from their seats." Transmission of energy by waves over a distance requires a medium; the media in the above examples were water and air; sound cannot travel through a space devoid of air. We know no other methods of energy transmission. Hence, the light which conveys energy to the Earth from the Sun must either be a stream of particles, and/or a system of waves in some medium. Such views were current in various forms with the ancients. And they were inevitably to come up

again in later days when physicists attempted to combine all the diverse properties of light into a uniform theory.

Newton did his best not to confuse conjecture with established fact, assumptions with reality, but in his works he returned many times to the question of the nature of light, inclining towards the emission theory. His chief argument against the wave theory was the absence of the material medium "ether" in universal space. Indeed, the planets move with absolute regularity, without encountering any perceptible resistance or friction in the space surrounding them; therefore, there are no grounds to assume any material medium, necessary for the propagation of waves, to exist in the space between the planets and the Sun. Just like sound, which ceases to exist in a vessel from which the air has been exhausted, so with the mechanical vibrations of luminaries which cannot become waves in the "void" of interplanetary space. According to Newton, the assumption of light being a stream of minute particles of substance is the more probable one.

Periodicity, according to Newton, might be due, for instance, to the particles rotating. The space this particle, or corpuscle, covers in the time it makes one revolution would then be the "wave-length." Newton considered polarization a property peculiar only to solid particles, and held this property of light to be proof of its consisting of solid corpuscles. He attempted to attribute the diffraction (the bending) of light to its being attracted and repelled by substance.

But Newton's own experimental heritage contained a very difficult obstacle for his mechanical theory of light particles. There can be no doubt that Newton's rings in the experiment we have already mentioned (p. 23) appear as a result of the interaction (interference) between two rays that meet after having been reflected from the upper and lower boundaries of the air layer between

the lens and the glass. Let us consider two such rays (fig. 11).

Ray *1* is reflected from the upper boundary, giving the reflected ray *1*; ray *2*, after being refracted at the upper surface, is reflected from the lower, and then enters the lens again. These rays meet, "interfere," and thus produce the constant figure of Newton's rings. Now, let us assume with Newton that rays *1* and *2* are the paths of light particles, emitted chaotically by a luminous source. The particles are absolutely independent of one another. If a very feeble illumination is applied, we should be able, finally, to reach a state where the probability of the particles travelling along paths *1* and *2* simultaneously becomes negligible. If Newton was right, in this case the rings should disappear, the particles having nothing to interfere with. But the experiment with Newton's rings gives the same result, no matter how low the intensity. For instance, the illumination can be so low that it takes several days' exposure to photograph the rings, and still they are just as distinct as with strong illumination.

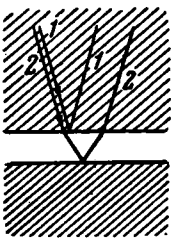

Fig. 11. Paths of rays in Newton's experiment with interference rings

One hundred and fifty years had to pass before it was proved that the difficulty in explaining the ring experiment and analogical interference phenomena could be overcome by assuming light to be an undulatory motion. Indeed, waves propagate from the luminous point in all directions and convey some amount of energy in all their parts, whatever the intensity; hence, rays *1* and *2* can always interfere. Moreover, the wave theory foretells the result of the interference very accurately: if the phase difference of the waves at the point they meet is such that the trough of one falls exactly on the crest of the other, the two waves extinguish each other at this

point, forming a dark ring; on the other hand, in the neighbouring section, where the crests of the two waves come together, they enhance each other, and a bright ring results.

The new theory of light waves was just as successful in explaining all the niceties of diffraction; it foretold facts which experiment never failed to confirm to the letter. The wave theory also gave a clear explanation of light polarization. The phenomenon of polarization shows

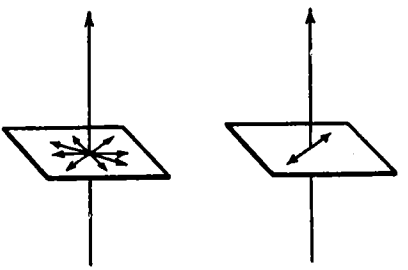

Fig. 12. Vibrations in polarized and nonpolarized light

that light waves are transverse, i.e., that the vibrations are perpendicular to the direction of the ray, just as in the case of water waves on the surface of a pond. Unpolarized rays vibrate in all directions around the ray (fig. 12), whereas polarized rays vibrate only in one direction.

In the first half of the XIX century the wave theory triumphed over the Newtonian emission theory, owing to the irreproachable qualitative and quantitative accuracy of its predictions. But was this victory stable? It must be remembered that Newton's main argument against the wave theory was the absence of a mechanical medium—ether—in interplanetary space. Had Young and

Fresnel defeated this argument? No, they had not; they considered that the undulatory properties of light precisely proved the existence of ether. Throughout the whole of the XIX century physicists strove in vain to find direct evidence of the existence of ether. Experiments in the propagation of light through moving bodies proved especially fatal to the ether theory. If there exists an immobile mechanical medium through which light waves are propagated, then the annual rotation of the Earth around the Sun should be accompanied by a sort of "ethereal wind" which should influence optical phenomena. Practically, however, no such "wind" was found to exist. Consequently, there is either no ether, or else it possesses entirely specific properties, not common to mechanical phenomena.

In spite of this, the wave theory of light received support quite unexpectedly from the field of electrical and magnetic phenomena. It was proved by experiment that electrical and magnetic disturbances are propagated with the velocity of light, the relation between the electrical and magnetic states being such that under certain conditions electromagnetic waves must be propagated through space. Predicted theoretically by Maxwell, these waves were observed experimentally by Herz. A. S. Popov first discovered how to utilize electromagnetic waves as a powerful means of signalization over long distances, thus founding radio. P. N. Lebedyev and other scientists showed that electromagnetic waves possessed all the properties of light known at the time—they could be reflected, refracted, polarized and were capable of diffraction. In this way a new property of light was discovered—it was found to be an *electromagnetic phenomenon.* This explained the interaction between light and substance. As we know very well now, substance is built up of electrically charged particles, of positive nuclei with negative electrons around them. The movement of these particles should give rise to electromagnetic waves,

i.e., to light. On the other hand, when electromagnetic waves hit atoms and molecules, they put the charged particles into motion, the energy of the waves being dispersed and absorbed.

Now let us return to the difficulty with ether. In the mechanical wave theory of light ether is absolutely indispensable; without a medium, without ether, there can be no mechanical waves, just as without air or some other medium there can be no sound. But as soon as it was shown that light waves are electromagnetic the situation became entirely different. Irrespective of whether ether exists or not, we find from direct and well-known experiments that charged bodies are surrounded by electrical fields. According to the laws of electromagnetism, if the charge begins to move, electromagnetic waves are sure to appear. The latter must exist, inasmuch as the electric field exists.

It might be asked, of course, whether the electric field itself can be explained without the ether conception. The only answer to this is that all the innumerable attempts to deduce the laws of electricity and magnetism from the conception of mechanical ether, beginning with those of Maxwell himself, have up till now been futile.

Irrespective of this, as we have already mentioned, the wave theory of light based on electromagnetism seemed to have been proved by the end of the XIX century beyond doubt, Newton's argument as to the nonexistence of ether having lost its significance as soon as it became clear that light waves are not mechanical in nature.

The wave theory, it seemed, had won the final victory. Everything in optics was "put into order." But this triumph was shortlived. In less than five years after the invention of radio the quantum laws of light action were discovered (p. 36). These laws were inconceivable from the standpoint of the wave theory. How can energy be absorbed in whole units if it is carried by uninterrupted

waves? Since then over 30 years have passed, and still this difficulty has not been overcome; the wave theory cannot answer the question to this day.

The wave theory is helpless before the quantum laws of light action. This inconvenience makes us recall what Lomonosov said in reference to the emission theory: "Inconvenience is often the next-door neighbour of impossibility."

On the other hand, it was precisely the "impossible" emission theory that now had the best chance of recognition. It knew none of the difficulties caused by ether: light corpuscles can travel through a vacuum, and are in no need of ether. The quantum laws also fully conform with Newton's theory. Molecules absorb light in whole quanta because they are struck either by a whole corpuscle, or not at all; for this reason in chemical changes caused by the action of light not all the molecules are decomposed at once, but only those which are struck by a quantum, a corpuscle. When we diminish the brightness of the waves, we decrease their swing, their tension, while in diminishing the flow of corpuscles we leave the action of each corpuscle unchanged, decreasing only their number. The quantum laws of light action in the emission theory infer only that light travels in whole quanta, or corpuscles.

But at the same time the revived emission theory was still unable to explain interference, diffraction and the other properties of light for which all difficulties were automatically removed by the wave theory.

The situation which consequently arose in optics became absolutely intolerable, and physicists had all grounds to repeat the sad words first uttered by Lomonosov in connection with the theory of light, and quoted at the beginning of this chapter. The two entirely different views on the nature of light reigned each in its own domain, remaining powerless in the neighbouring.

A ray of hope in solving this difficulty came from unexpected quarters. Let us recall how we came to the conclusion that only two conceptions of light were possible. We proceeded from habitual everyday observations, which showed that energy could be transmitted mechanically only in two ways: by means of particles, or by means of waves. A combination of the two is, of course, conceivable, but these three ways are the only ones that can be "imagined" and "understood."

Classical mechanics, which, like optics, was founded by Newton, is a mathematical generalization of our habitual experiences, and its conclusions, as far as the possible ways of energy transmission over long distances are concerned, do not differ from our simple deductions. So-called "classical physics" is quite confident that the Laws of Newton are ultimate truths, beyond all doubt. This certainty gave rise to the "mechanistic" natural science, which tried to explain all natural phenomena through the movements of particles bound together by means of certain forces and subject to the Newtonian Laws.

The confidence in the infallibility of these laws was based, primarily, on their *comprehensibility*, their full conformity with our habitual, extra-scientific conceptions, secondly, on the *success* of classical mechanics in all fields of natural science and engineering. However, these arguments in favour of the Newtonian Laws are far from irreproachable. We call "comprehensible" what conforms with our habits. For instance, we compare a flying atom with a flying bullet, thus picturing the atom through the more familiar image of the bullet. But it is quite clear to anyone that in reality the bullet is immeasurably more complex than the atom, and that we have been "reducing" a simpler thing to one more complex, though more familiar. "Comprehensibility" of laws and phenomena is no proof of their real simplicity and truth. On the other hand, man develops as time goes on, his habits

change, and what was formerly incomprehensible gradually becomes obvious. Our familiar ideas correspond to a great extent to the true course of phenomena and as man develops he comes closer and closer to apprehension of the truth; but to claim full coincidence of our ideas with absolute truth means to deny the unquestionable truth that mankind is continuously developing. To put it briefly, the belief in the mechanicalness of nature and the infallibility of the Laws of Newton is built, in the main, upon the very shaky foundation of "habit."

Apparently insurmountable internal contradictions were discovered at the junction of the XIX and XX centuries not only in light phenomena, but in the properties of matter as well. The mass of a body was found to be dependent upon its velocity; even the ideas of space and time were found to require revision. There appeared physicists and philosophers who began to speak of the "dematerialization" of matter, asserting that "matter had disappeared—and only equations remained." The fact that mechanistic, metaphysical materialism had come up against difficulties and contradictions in the course of its consistent development caused some scientists to reverse their positions, passing over frankly or disguisedly to the haze of idealism and mysticism. This was fomented also by the social conditions of the moribund capitalist world; the haze of idealism is one of the smoke screens concealing the violence, fraud and instability of capitalist society from progressive humanity.

But metaphysical materialism, the embodiment of which was supposed to be "classical physics," and the new physical idealism it gave rise to, were overcome by dialectical materialism, the teachings of Marx, Engels, Lenin and Stalin. V. I. Lenin gave a profound analysis of modern physics from the standpoint of dialectical materialism in his famous book *Materialism and Empirio-Criticism* which appeared in 1909.

The principal features of the dialectical method of studying nature are that it regards nature as a connected and integral whole, in a state of continuous movement and change. "Any phenomenon in any realm of nature may become meaningless to us if it is not considered in connection with the surrounding conditions, but divorced from them..."* writes J. V. Stalin in his synthetizing work *Dialectical and Historical Materialism.* "Contrary to metaphysics," says J. V. Stalin, "dialectics holds that internal contradictions are inherent in all things and phenomena of nature, for they all have their negative and positive sides, a past and a future, something dying away and something developing."**

V. I. Lenin showed, in his *Materialism and Empirio-Criticism,* that the metaphysical, mechanistic idea of matter must be replaced by the broad, vivid dialectical conception of matter as an objective reality. Such a conception cannot but include any property of nature with its contradictions and complexities, provided the property really exists.

From this standpoint, the "insurmountable" contradiction between the undulatory and corpuscular properties of light phenomena which arose as a result of the development of optics is a new manifestation of the dialectics of nature, of the true unity of opposites. The simplified mechanical conceptions of continuous waves and discrete particles, which, according to classical physics mutually exclude one another, get along quite well together in real natural phenomena. This unwonted contradictory unity only displays the insufficiency and primitiveness of our mechanical ideas. The matter of the real world is infinitely more complex than the metaphys-

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* *History of the C.P.S.U.(B.). Short Course,* Moscow 1954, p. 168.

** *Ibid.,* p. 172.

ical images we have conjured up for ourselves by force of habit and long experience.

The progress of science has confirmed this. The achievements of classical mechanics together with the high perfection of experimental technique ended in the impotence and helplessness of this mechanics before new facts.

We conceive the existing material world—matter in motion—in two fundamental forms, as *substance* and as *light*. We have gradually come to the conviction that substance in all its diversity of form consists of negatively charged electrons, positively charged protons, and neutrons, which have no charge at all. For this reason substance seemed easier to understand than light, which displayed at once the properties of both waves and particles. While motion is an inseparable property of light, and the very idea of "immobile light" seems absurd, mechanical physics had no objections to "substance at rest." Waves are inconceivable without motion. When a physicist says "standing waves," he means the result of two similar undulatory motions being transmitted simultaneously in opposite directions. On the contrary, an individual particle can be conceived to be completely at rest. But from the standpoint of dialectical materialism matter deprived of motion, i.e., of its inalienable property, is a pure abstraction. And so, indeed, it is, as recent quite unexpected and remarkable experiments have shown. In experiments first performed somewhat over a quarter of a century ago, it was found that when streams of electrons, protons and molecules come across small obstructions or pass through small apertures in their path, they produce just as distinct diffraction phenomena as light, i.e., they possess the same principal undulatory properties as the latter.

Fig. 13 shows the diffraction pattern produced by electrons upon passing through a very thin layer of silver made up of microscopic crystals. In this case the pattern

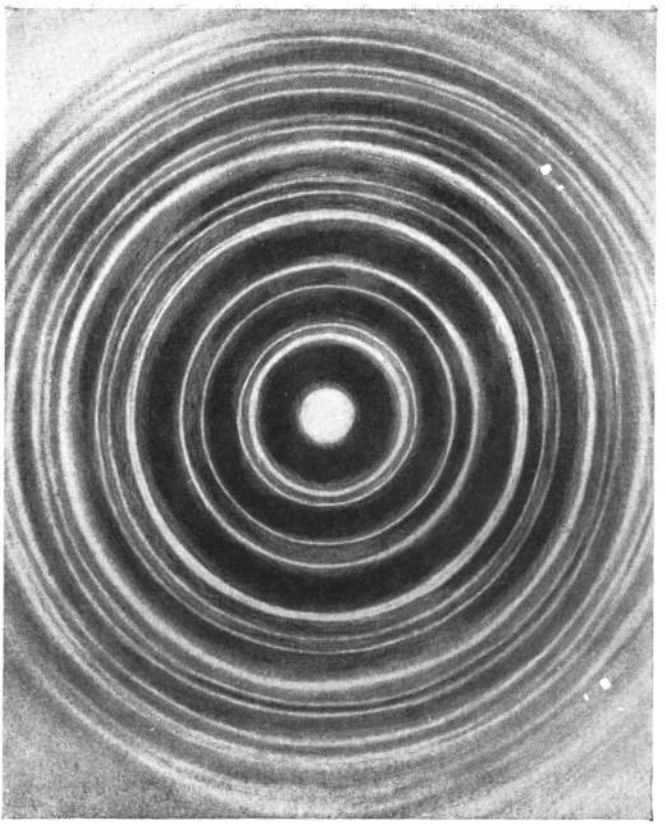

Fig. 13 Diffraction of electrons upon passing through a very thin layer of silver

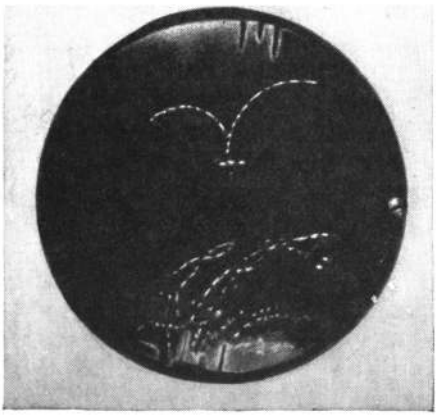

Fig. 14 Formation of an electron-positron couple from a gamma light quantum. In the magnetic field (above) the positron deviates to the left, and the electron to the right (photograph by A. V. Groshev and I. M. Frank)

is no less distinct than with light, and is just as good evidence of the undulatory nature of electrons, i.e., substance.

At present the length of these "substance waves" can be measured with great accuracy; they have been found to equal h/mv, where h is the same constant we came across when considering the properties of light (p. 36), m—the mass of the particle and v—its velocity.

It may be assumed that not only elementary particles—electrons, atoms, molecules—correspond to waves. There are grounds to affirm that any individual accumulation of substance, whether it be a man, a tram or the Sun, can be characterized by a wave corresponding to its mass and velocity.

It is difficult to point out another discovery in all the history of precise natural science so unforeseen and so sharply contradictory to our habitual conceptions.

The same happened in mechanics as in optics. The ancient science of light considered a light beam to be a sheaf of rays travelling in straight lines, but the diffraction phenomena it displayed made it evident that light is an undulatory motion which behaves like a pencil of rays if there are no small obstructions or apertures in its path. Wave optics was hidden behind the ostensible geometrical ray optics. Newton's mechanics was a "ray mechanics," but discoveries made in our times have shown that it hides a more general "wave mechanics."

"Substance waves," however, should not be identified with light waves. We have seen that light waves are of an electromagnetic nature, which cannot be said of the waves of substance. The latter coincide organically with substance and the particles it consists of, while light waves are radiated, are given off by substances and have entirely different properties.

It would also be wrong to think that the theory of particles has been replaced by a more correct theory of waves. The existence of particles of matter, atoms and

electrons in substances, quanta in luminous fluxes, is just as true as the existence of waves of substance and light. There have been attempts to treat matter as a mechanical combination of particles and waves; in this scheme the waves only play the part of the pilot, directing the particle according to the laws of wave propagation. At first sight, an inverse mechanical treatment is also possible, according to which the waves are caused in ether by the particles, in the same way as the swells raised in the wake of a ship. These assumptions, however, led to conclusions which had nothing in common with reality.

There is a rather widespread opinion that in some types of experiments (e.g., in that with Newton's rings) light behaves entirely like an undulatory motion, while in others (such as the fading of a dyed fabric) light acts entirely like a stream of particles. This is, however, a mistake. If Newton's experiment is performed with a very dim light, it is possible under certain conditions to observe irregular statistic oscillations of the brightness of the light rings, which shows that in this typically undulatory phenomenon the luminous energy is also concentrated in individual centres—photons. On the other hand, if a dyed fabric is subjected to the action of light falling through thin slits, it will show diffraction patterns upon fading.

Matter, i.e., substance and light, possesses the properties both of waves and particles simultaneously, but, on the whole, it is neither waves nor particles, nor a mixture of the two. Our mechanical conceptions are incapable of grasping reality in full, there being no visual images to aid us.

A formal mathematical theory of light, though not quite perfect, has been deduced at present, embracing almost the entire sphere of known phenomena. This theory, however, is still very abstract and "incomprehensible" (in the sense of there being no visual images).

Now we may return to the difficulty we met with at the beginning of this chapter. The reader has probably not forgotten the trouble we had in attempting to define the subject embraced by the science of light. Has this question become clearer now? In principle, yes. We have gradually established the chief objective properties of light, which distinguish it from other kinds of matter. But the practical application of these distinguishing features, especially when they are taken all together, is still rather difficult in some cases.

At the end of the last century physicists could not for quite a long time come to a decision as to whether cathode rays were substance or light. The question was solved when it was shown experimentally that cathode rays have a negative charge. The fact that X-rays are of the same nature as light rays was also considered dubious for a long time. Only after X-ray diffraction patterns had been observed in 1913 did physicists finally agree that this was so. Strictly speaking, however, this conclusion should have been put to test again after diffraction had been observed with beams of charged particles, electrons, and protons, and with uncharged particles, neutrons, as well. After all, it is only the aggregate of all the various phenomena demonstrating the electromagnetic properties of X-rays that proves their luciform nature.

In the course of several decades research workers kept radically changing their minds as to the nature of the so-called cosmic rays, which are continuously coming to the Earth from all directions out of universal space, and have immense penetrative power. Two decades ago it was considered established that cosmic rays consist mainly of light rays of very small wave-length, shorter, on the average, than the gamma rays emitted by radium. Later, however, it was shown that cosmic rays are deflected by the magnetic field of the Earth, and therefore consist of electrically charged particles. At

first, in connection with this, it was assumed that primary cosmic rays were made up of electrons. But recent studies, especially the experiments of Soviet physicists, carried out in the upper layers of the atmosphere, have proved beyond doubt that primary cosmic rays consist chiefly of positively charged protons. It should be noted that cosmic rays have very high velocities, practically equal to that of light.

These examples show clearly how difficult it sometimes is in practice to prove any phenomenon to be definitely of a luciform nature.

The inexhaustibility of the essence of real matter in its various forms, of substance and of light, becomes more and more evident as scientific research delves further into the depths of phenomena. In spite of the great number of common properties (the properties of waves and particles, the quantum laws), we have up till now considered light and substance essentially heterogeneous, differing approximately as the sound differs from the violin emitting it, as wireless waves differ from the radio transmitter. But about twenty-five years ago one more striking discovery was made in the science of light.

On the basis of the formal mathematical theory of light mentioned above, its author, Dirac, came to the theoretical conclusion that under certain conditions light should turn into substance and vice versa. In the strong electric field of the atomic nucleus light quanta with wave-lengths of no more than about 0.001 mμ, according to Dirac, can decompose into two particles with opposite charges—an electron and a positron. Astounding as it was, this theoretical prediction was, nevertheless, fully confirmed in practice. The transformation of light into substance was proved experimentally. In fig. 14 we see a photograph of this striking process. The possibility of taking such a photograph is based on the fact that fast charged particles, in passing through air saturated with water vapour, leave traces formed by condensed droplets

of water. The oppositely charged particles, the electron and the positron pass through a strong magnetic field, as a result of which their paths are bent in opposite directions.

The photograph shows the amazing phenomenon of a luciform gamma ray turning into two particles of substance. This is, indeed, something like the fantastic transformation of the melody into the violin!

So far science has no other means of explaining this phenomenon than the formal, and therefore unsatisfactory, Dirac theory. Just the same, a profound, hitherto unsuspected relation between light and substance has been disclosed. Man has mastered one more aspect of nature.

* * *

Starting out from the subjective visual sensations of colour and brilliancy, we have followed the history of optics step by step, and have finally come down to the present-day complex state of the objective science of light. The reader is probably dissatisfied with the end of the story about the development and fate of the different views on the nature of light. The riddle has not been solved yet, in the usual sense of the word, and has only become still more complicated than it seemed in the times of Newton and Lomonosov. But such is the fate of any field of real science. The closer we approach the truth, the more evident its complexity becomes and the more obvious its inexhaustibility. Science's ceaseless battles for the truth, victorious, but never finally triumphant, are, nevertheless, undeniably justified. On his way to the apprehension of the nature of light, man has come to the microscope, the telescope, the range-finder, radio, X-rays; his investigations in this field have helped to harness the energy of the atomic nucleus. In his search for the truth man boundlessly extends the domain of his mastery over nature. And is this not the real purpose of science? We

are certain that the history of the study of light, its nature and essence is far from completed; there can be no doubt that new discoveries in this field await science in the future, that we shall come closer to the ultimate truth, and that engineering will gain new means and methods.

The history of the study of light illustrates the sage words of J. V. Stalin:

"Contrary to idealism, which denies the possibility of knowing the world and its laws, which does not believe in the authenticity of our knowledge, does not recognize objective truth, and holds that the world is full of 'things-in-themselves' that can never be known to science, Marxist philosophical materialism holds that the world and its laws are fully knowable, that our knowledge of the laws of nature, tested by experiment and practice, is authentic knowledge having the validity of objective truth, and that there are no things in the world which are unknowable, but only things which are still not known, but which will be disclosed and made known by the efforts of science and practice."*

* *History of the C.P.S.U.(B.), Short Course*, Moscow, 1954. p. 178.

THE SUN

In the centre of everything is the Sun. Nor could anyone have placed this luminary at any other, better point in this beautiful temple, than that from which it can illuminate everything uniformly. Not without grounds, therefore, do some call it the World's Lamp, others—Reason, still others—the Ruler, Trismehist—the Visible Deity, Sophocles' Electra—the All-Seeing. Thus, the Sun is pictured seated on his throne, ruling over the family of stars around him.

N. COPERNICUS

There is a saying by Kozma Prutkov* which runs: "If it be asked of you: 'Which is more useful, the Sun or the Moon?' make answer: 'The Moon.' For the Sun shines in the day-time, when it is light enough without it, while the Moon shines at night." Of course, none of our readers are likely to be led away by this witty nonsense. It is light in the day-time because the Sun is shining, while at night the Moon gives its light by reflecting on to the Earth the rays of the Sun, which is shining elsewhere. We may shade ourselves from the direct rays of the Sun with a cap peak or parasol, but this does not keep the Sun from lighting up the air, the clouds, the fields and everything around us. The Sun may be hidden behind a

* Kozma Prutkov—the pseudonym of a group of Russian writers (A. Tolstoy, the Zhemchuzhnikov Brothers) who wrote comical verses, fables, aphorisms, etc., the distinguishing features of which were the accentuated absurdity, banality and poverty of the imaginary author's ideas.—*Tr.*

cloud, but its rays, scattered by the air, illuminate the Earth just the same. However, if a large opaque body happens to get between the Earth and the Sun at a large enough distance, it may not let the direct rays of the Sun pass into the Earth's atmosphere, and then the light vanishes. This is what occurs during solar eclipses, when the Earth, the Moon and the Sun come into a straight line. The essence of this phenomenon is illustrated in fig. 15.

The light that reaches man (including both visible and invisible rays) may be of three different origins. The *direct* solar rays that fall on Earth, are those we try to see as little of as possible. The axes of our eyes are usually directed horizontally, so that the Sun stands before the eyes only at sunrise and sunset. The rays that continuously reach our eyes during the day are *dispersed* solar rays. The blue of the sky is a result of the Sun's rays being dispersed by the molecules of the air. If the dispersing particles are very small, they mostly scatter rays with short wave-lengths (the blue and violet rays of the visible spectrum). If, however, the particles are larger they will scatter the longer waves as well to a considerable extent. This is easy to see when we light a cigarette. The smoke coming from the lighted end of the cigarette is blue, while that coming out of the mouthpiece is white. This is due to the fact that the smoke particles aggregate as they pass through the tobacco, i.e., become larger. For the same reason the scattered light coming from the clouds, which consist of comparatively large particles of moisture, is white, while the colour of the clear sky is blue. If the Earth had no atmosphere we should see the Sun against the background of a jet-black sky.

Observers looking out of the gondola of a stratospheric balloon at an altitude of 20-22 kilometres, saw over them an almost black sky with the Sun shining bright.

N. Copernicus (1473—1543)

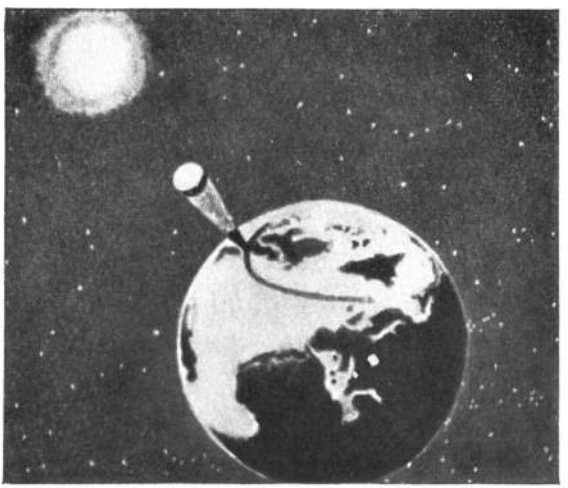

Fig. 15 Diagram of solar eclipse

Sunrise and sunset, the green of the fields and forests, the white of the snow, the gleaming of the Moon, is all reflected or dispersed sunlight.

But besides direct and dispersed sunlight we have to do with rays that are *independent* of the Sun. Any body emits light when heated. If it is heated very strongly the light emitted contains a lot of visible rays; if not, invisible infra-red rays are emitted, which can be detected only by their thermal effect. Everything around us contains heat. Although we say that this body is warm and that cold, we do so conventionally, meaning in relation to the temperature of our body. To deprive a body absolutely of heat would mean to stop the movement of its particles. This is possible only at a temperature of approximately —273°C (the absolute zero temperature). On the Earth, however, everything is warm, and therefore everything emits visible or invisible light rays; man himself also emits light, and so do his eyes. In this sense the ancients were right in attributing a "gentle inner light" to the eye. The energy of these inner rays of the eye is so great that if the eye could sense them as it does, say, green rays, it would constantly be accompanied, day and night, by a luminosity of 5 million candle-power intensity (cf. p.120).

Visible rays come to us from the stars, far-off suns and nebulae; from time to time flashes of lightning rend the heavens, or the fantastic aurora suffuses the sky. Fireflies gleam through the foliage on summer nights, rotten stumps phosphoresce in the forest. Together with visible light, lightning flashes emit invisible electro-magnetic waves; even during clear weather we hear strange crackling noises (static) over the radio which interfere with the programme—these are electro-magnetic atmospheric discharges. Such discharges led A. S. Popov to the discovery of wireless. In recent years it has been proved beyond doubt that the Sun and the stars also

emit radio-waves. These radiations often caused considerable trouble in the regular work of radar installations during World War II. There are certain substances in the Earth, called radio-active substances, whose atoms are constantly slowly disintegrating. This process is accompanied by the emission of gamma light waves with very short wave-lengths.

Besides this light which comes to us as a result of natural processes taking place on Earth and in the universe, man makes artificial light sources for himself when necessary. He lights wood, kerosene, candles, uses incandescent electric lamps, in which metallic filaments are heated by electricity. In the modern, more perfect luminescent lamps the electric current first causes a discharge in mercury vapours, which is accompanied by the emission of ultra-violet rays. The latter are then absorbed on the walls of the glass tube which is coated on the inside with a luminescent compound, and are transformed into visible light. Every radio-broadcasting station is a luminous source in its way, emitting very long waves. X-ray tubes made for scientific and medicinal purposes radiate invisible light which passes easily through the human body.

But the energy of all these sources of light, whether taken separately or together, is really infinitesimal when compared to the luminous energy of the Sun. It must be remembered that in the long run, when we light a lamp, or put a radio-station or an X-ray tube into operation, we are using an infinitesimal part of the solar energy accumulated by plants in the form of coal, petroleum and wood. When we utilize the energy of the wind, waterfalls or reservoirs we are again using the luminous solar energy which caused the wind or lifted the water. Hence, it is clear that not a single artificial source can compare with the Sun in the total amount of energy radiated.

The reason why man uses his own humble artificial

light sources alongside the Sun, not only at night, but in the day-time as well, is that the spectral composition of the light, one of its fundamental properties, is frequently just as important as the quantity of luminous energy, if not more so.

We know that this very important idea of the spectral composition of light was first introduced by Newton. The prism apparatus by means of which he resolved solar

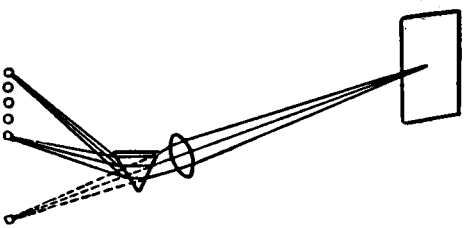

Fig. 16. Diagram of spectroscope
(After drawing by Newton.)

light became the prototype of all the various kinds of *spectroscopes* used in science at present and in the past. Fig. 16, which is a copy of Newton's original drawing, gives a clear idea of the simple Newtonian spectroscope. Light falls on a narrow slit situated almost at the focus of a lens on the other side of it. The light beam, passing through the lens, falls on the prism, is refracted and then enters a small telescope adjusted to "infinity." The image of the slit of the spectroscope can be seen through the eyepiece of the telescope in each of the simple colours the complex colour under investigation consists of. If the slit were very wide the images would overlap and the simple colours would mix somewhat, making the spectrum diffuse.

If a kerosene or electric lamp is placed before the slit of the spectroscope, we see a continuous sequence of

colours through the telescope, from red to violet. If a photographic plate is put in front of the eyepiece a short ultra-violet continuation will be found to follow the violet end. But neither the eye nor the plate are of any use in judging about the distribution of energy across the spectrum; they have their narrow ranges of especial sensitivity, outside of which they are almost insensitive.

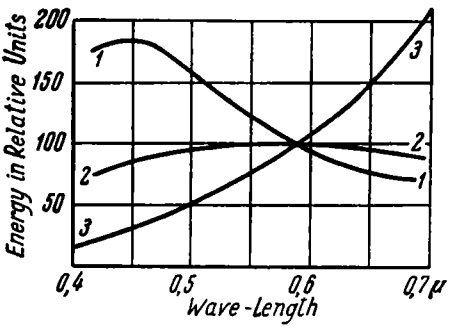

Fig. 17. Distribution of energy in the spectra of various sources

The eye is especially sensitive to the green part of the spectrum, and an ordinary photographic plate—to the blue and the violet. The best way to judge about the energy of the spectrum is to use a thermal instrument which completely absorbs rays of any kind, converting them into heat (a thermo-element). Unfortunately, such instruments, even when made very accurately, are far less sensitive than the eye or a photographic plate. Fig. 17 shows the distribution of energy measured in this way for several light sources. The wave-lengths in microns are computed along the horizontal axis (we remind the reader that 0.4μ corresponds to the violet limit of the spectrum, and 0.7μ—to the red limit). The energy in relative units is computed along the vertical axis, accepting the energy at 0.59μ for each source conventionally

as 100. Graph *2* gives the energy distribution in the visible part of the solar spectrum, graph *1*—in the blue light of the sky; it can be seen that as a result of dispersion the energy maximum has shifted into the blue zone. Graph *3* gives the distribution of energy in the spectrum of an electric lamp.

If different solids, for instance, metals, are heated to the same high temperature, their energy distributions will differ somewhat. This difference is due to the unequal reflectivity of the solid surfaces. If the surfaces are made absolutely black, so that they completely absorb all the rays and reflect none, the energy distribution at equal temperatures will be the same for all solids.

In a heated body the energy of molecular movement is transformed into light and, on the other hand, light is absorbed by molecules. At any given temperature the amount of light absorbed comes into equilibrium with the amount emitted.

In the chapter on light we came to the conclusion that the emission and absorption of light can occur only in whole quanta, $h\nu$. If the equilibrium between the emission and absorption by a body with an absolutely black surface is considered, taking into account the quantum nature of both processes, the law of energy distribution of the light emitted by a black body can be deduced quite strictly without great difficulty. Historically this problem was solved the other way around. In search of a true spectral law of radiation by black bodies, which would conform with experimental data, Planck first came to the conclusion that such a law could not be deduced without the assumption that light is emitted and absorbed in whole quanta. This is how the far-going quantum laws of nature were discovered.

Fig. 18 shows the law of "black radiation" for several temperatures. The abscissae are the wave-lengths of the light rays in microns ($1\mu = 1{,}000\ m\mu$), and the ordi-

nates—the intensity or energy in relative units. The shaded area corresponds to the visible range of the spectrum. As the figure shows, the maximum of the spectral curve shifts towards the short-wave end as the temperature rises. This conforms with the well-known fact that

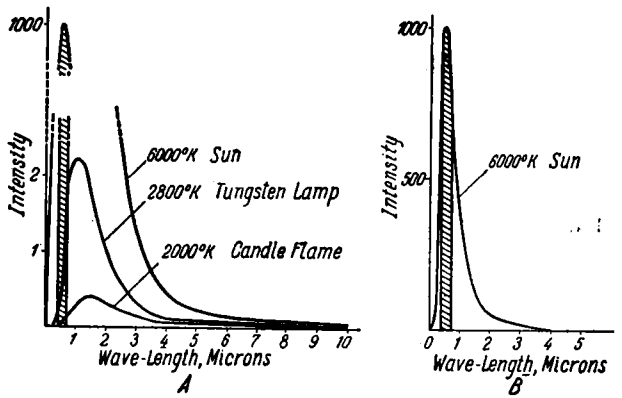

Fig. 18. Distribution of energy in the spectrum of the radiations of a black body at various temperatures. (Owing to the immense difference in the intensities, the graph for 6000°K could not be represented to scale in fig. 18a. The complete curve for this temperature is given in a smaller scale in fig. 18b.)

as the temperature of a metal rises it gradually turns red and then white. The theoretical law of energy distribution in the spectrum of a black body is confirmed by experiment to the highest degree of precision attainable at present. A particular corollary of this law is that the product of the wave-length λ corresponding to the maximum of the spectral curve by the absolute temperature T (i.e., the temperature in Centigrade degrees plus 273), is a constant:

$$\lambda_{max} T = K = 2897.18 \text{ microns/deg.}$$

If the value of λ_{max} (in microns) is known, this formula can be used to determine the temperature of the body.

We turned to the spectral distribution of light in connection with the quality of solar light. The Sun is most decidedly a strongly heated body, and therefore its spectrum should be similar to those produced on Earth by our lamps and candles. Indeed, when observed through a poor spectroscope with a wide slit, the solar spectrum seems continuous. When measured roughly the distribution of energy in this spectrum follows one of the black radiation curves (fig. 18). The approximate temperature of the Sun's surface can be computed from the shape of that curve and the position of its maximum if it is assumed to be similar to a strongly heated black body. In this way the Sun's temperature is found to be about 6000°. It would be of little use to determine the figure more accurately, since different parts of the Sun's disk have different temperatures.

As to distinguishing the quality of light, our eye is much inferior to the very worst spectroscope. Hence, the rough figure given will be accurate enough for the comparison of the properties of sunlight with those of the eye to be made in the following chapter.

In studying the Sun physicists and astronomers employ telescopes and high-precision spectroscopes, and mostly use photography instead of the eye. In this way they are able to disclose details in sunlight and its distribution over the Sun that completely escape the unaided eye.

In 1802 Wollaston discovered a property of the solar spectrum which for some reason had entirely escaped the attention of Isaac Newton. He found that the spectrum was interrupted by a large number of thin black lines. Later these dark chasms on the bright background of the solar spectrum were studied in detail by Fraunhofer, and are now called the Fraunhofer lines, after him. The most important of these lines in the visible part of

the spectrum are given in Table 1. As they always remain in their places they can serve as natural "landmarks" on the solar spectrum and are often used to denote its various regions.

Table 1

Line	Wave-Length, mμ	Colour	Source
A	759.4	Red	Oxygen in the Earth's atmosphere
a	718.5	„	Water vapour in the Earth's atmosphere
B	686.7	„	Oxygen in the Earth's atmosphere
C	656.3	„	Hydrogen on the Sun
D_1	589.6	Yellow	Sodium „ „ „
D_2	589.0	„	„ „ „ „
E	527.0	Green	Calcium „ „ „
b_1	518.4	„	Magnesium „ „ „
b_2	517.3	„	„ „ „ „
b_4	516.8	„	„ „ „ „
F	486.1	Blue	Hydrogen „ „ „
g	430.8	Violet	Calcium „ „ „
H	396.9	„	„ „ „ „
K	393.4	„	„ „ „ „

The second column gives the wave-lengths in millimicrons, and the third—the colour of the spectral region in which the line is located.

It has been mentioned above that, observed through a poor spectroscope, the Sun's spectrum seems continuous, and the energy distribution curve regular and smooth. A detailed study of the distribution curve, however, shows that it is all jagged with notches both in the visible and invisible regions (fig. 19). These notches are traces of the Fraunhofer lines. In the ultra-violet region the Sun's spectrum ends quite abruptly, the limit varying with the time of day and the season of the year. Rays

from the Sun with wave-lengths below 290 mμ practically do not reach us. All the shorter waves are absorbed by the ozone in the upper layers of the atmosphere with a maximum of about 19 miles.

How is the absence of certain colours in the solar spectrum to be explained? If common salt is introduced into a colourless alcohol or gas flame, the flame turns bright yellow. Viewed through a spectroscope (a good one), the continuous spectrum will be found to have

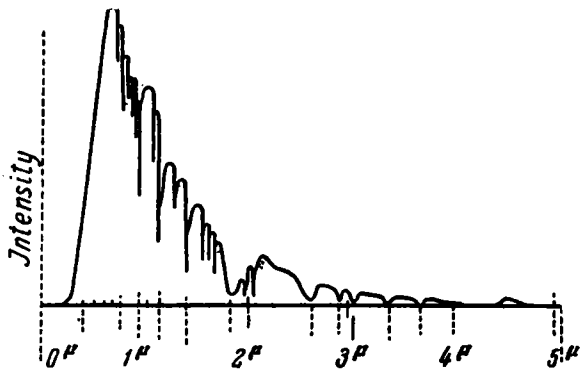

Fig. 19. Distribution of energy in the solar spectrum

almost entirely disappeared. Its place is taken by two yellow lines side by side, with wave-lengths that coincide exactly with those of the Fraunhofer lines D_1 and D_2. This coincidence is so accurate that it cannot be attributed to chance. The difference is that while the flame gives bright lines on a dark background, the Sun gives black lines on the brilliant background of the spectrum.

In the flame salt decomposes into chlorine and sodium, the latter causing the luminous effect. It is natural to assume that the black D-lines in the solar spectrum are also caused by sodium vapours. Indeed, if a vessel with metallic sodium vapours or a gas flame coloured with

salt is placed in the path of a continuous spectrum, say, that of incandescent electric lamp, the regions corresponding to the D-lines become weaker; we shall have produced Fraunhofer lines artificially on the background of a continuous spectrum. Consequently, sodium vapours can both absorb and emit D-lines: to be on the safe side, it should be said that the great majority of atoms in sodium vapours are capable of absorbing light. But having absorbed the light quanta of the D-lines, the atoms become "excited," stop absorbing radiations, and after a time give off the energy they have entrapped, in the form of light. In other words, the strongly heated salt vapours contain normal sodium atoms, which absorb light, and excited atoms, which emit the light they have previously absorbed.

A luminosity consisting of separate thin spectral lines can be excited in one way or another in the vapours of any of the elements. The number of such lines may be very large. This shows that the atom can be in a large number of different states of "excitement."

It was found that both atomic line spectra and the continuous spectra of black bodies obey the quantum laws. This means, in particular, that the same quantum constant h holds for both. On the other hand, line spectra are expressions of the inner structure of the atoms they represent. Hence, atomic structure, like light, obeys the quantum laws. Quantum relationships manifest themselves also in the spectra and structure of molecules. In a highly rarified gaseous state molecules emit "band" spectra. By means of spectral instruments these bands can be divided up into a great number of very thin lines. The locations of these lines are in conformity with quite simple quantum laws. Thus, once again we have convincing evidence of the fact that light and substance have some very important kindred properties in common.

Now, let us return to line spectra. Each element, as we have seen, has its own optical "landmarks"—spectral

lines, whose location can be measured exactly and which are difficult to confuse with those of any other element. Thus, without leaving the Earth, we can study the chemistry of the Sun and other luminaries by their spectra. The vapours of the elements constituting the Sun's atmosphere leave traces in the form of Fraunhofer lines on the continuous spectrum of the Sun's core, which passes through these vapours on its way to the Earth. The last column of Table I shows the elements the lines correspond to.

Some of the lines are a result of the Sun's light being partially absorbed by the Earth's atmosphere, which is also noted in the Table. Most of the chemical elements found on Earth have been discovered on the surface of the Sun as well. Those not discovered are chiefly such heavy elements as gold, mercury, thallium, bismuth, radium, etc.

In fig. 20 the quantities of atoms of various chemical elements in the Earth's crust (x's) are compared with those on the Sun's surface (o's). The figures at the left are the logarithms of the relative quantities of the elements, which means that the figure 5, for instance, denotes 10^5 atoms. It can be seen that the relative quantities of some of the atoms on Earth differ widely from those on the Sun's surface. On the other hand, the figures for such elements as sodium, silicon, calcium and strontium almost coincide. The absence of spectral lines is not evidence enough to consider the element absent. The lines may lie in the ultra-violet region which does not reach the Earth. The ultra-violet region of the Sun's spectrum is concealed from the observer on Earth mainly by the ozone in the Earth's atmosphere, which concentrates mostly in the stratosphere at an altitude of 12-19 miles.

After World War II several V-2 rockets, captured as trophies in Germany, were used in the U.S.A. to photograph the solar spectrum from altitudes beyond the ozone layer. Fig. 21 shows photographs of the spectrum taken

automatically from the rocket at various heights. The altitude (in kilometres) is shown at the left, and the wave-lengths in millimicrons are computed along the abscissa axis. It may be seen that at altitudes of 25 km. and more the spectrum becomes longer in the direction of the ultra-violet. The spectrum photographed at 34 km.

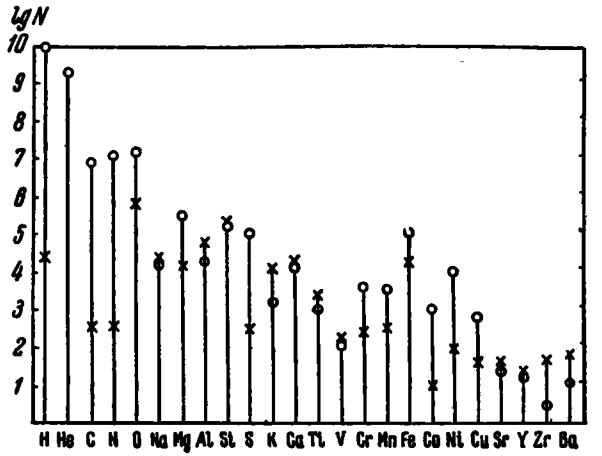

Fig. 20. Comparison of the mean relative number of atoms of various chemical elements on the Sun's surface and in the Earth's crust

extends out to 280 mμ, where it breaks off, however, quite abruptly. At greater altitudes up to 55 km., a new wide range of the spectrum, down to about 240 mμ, comes into view. The dark band at 280 mμ persists, however. It corresponds to absorption by magnesium vapours.

Not only atoms have been found on the Sun, but the simplest molecules as well, such as OH, CN, CaH, H_2, etc.

The dimensions of the Sun are enormous: its diameter is almost 1,400,000 km., i.e., 110 times that of the Earth, and its volume is 1,305,000 times as large. But the Earth is much denser: the average density of the Sun is 1.406

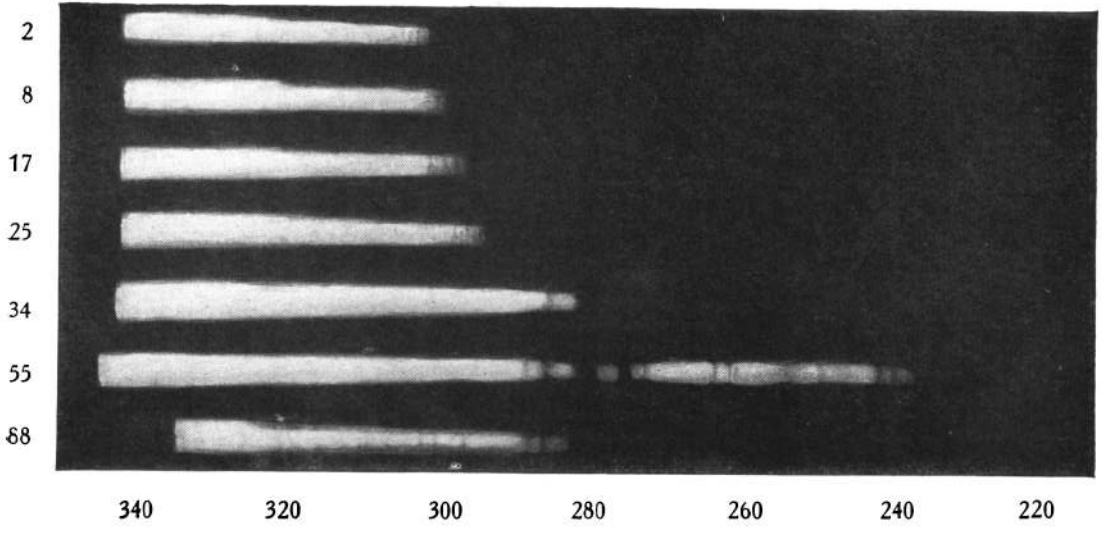

Fig. 21 Solar spectrum photographed from rockets at various altitudes

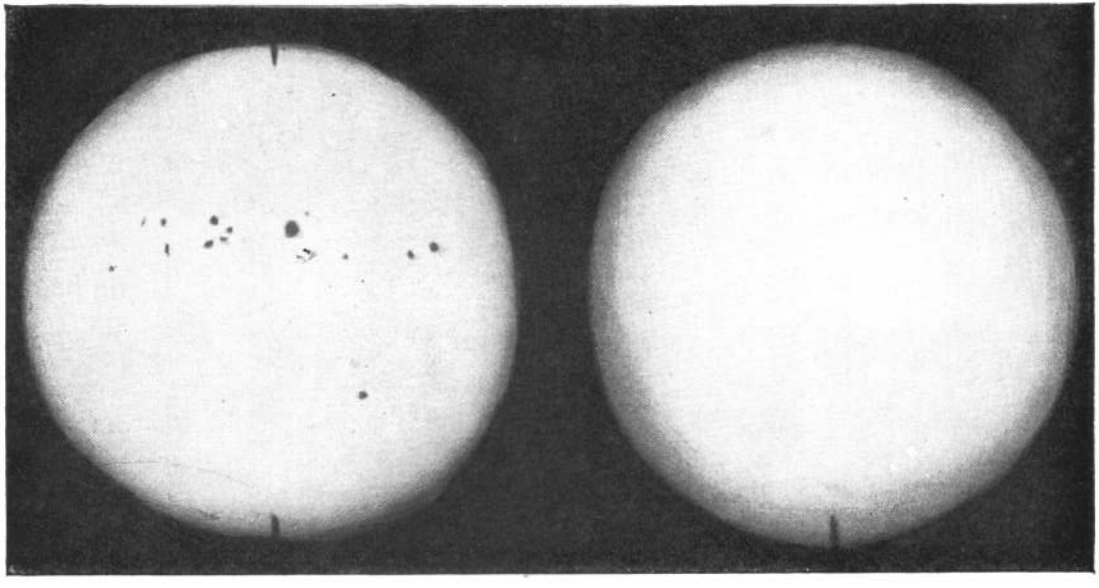

Fig. 22 The solar disk with maximum (right) and minimum number of sun spots

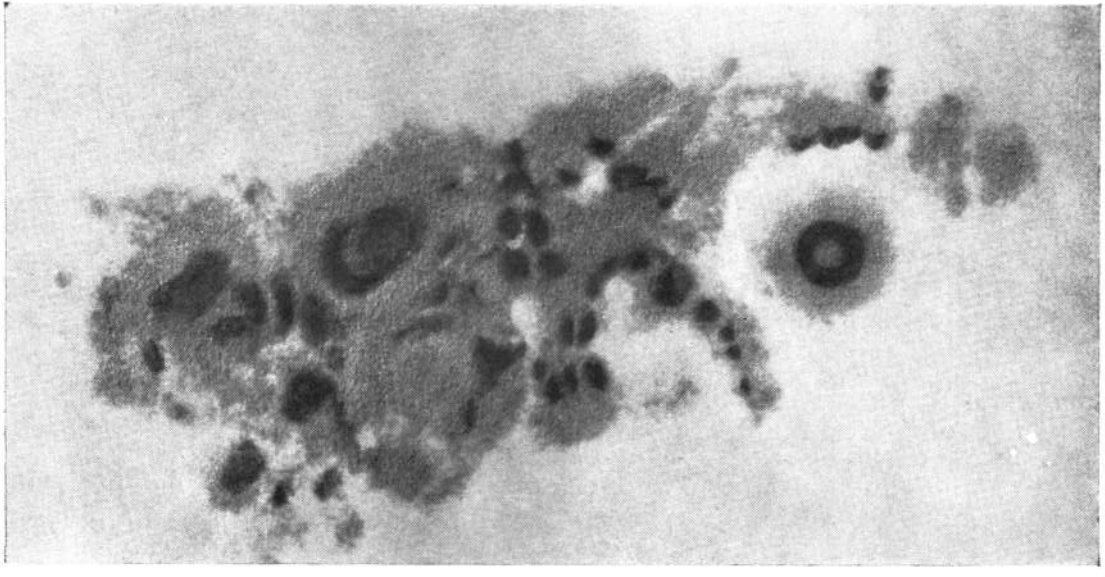

Fig. 23 View of a group of sun spots

times greater than water, while that of the Earth is 5.6 times as high. The total quantity of matter in the Sun is 330,420 times the quantity in the Earth. The weight of solar substance in tons constitutes the rather vague figure of 2×10^{27} (meaning that the 2 is followed by 27 zeroes); if the Sun were to lose weight at a rate of 1,000 million tons per second, it would take it 30,000 million years to reduce to one-half of its present "corpulence"!

We know this tremendous accumulation of matter only from the outside. The internal life of the Sun is unknown, and can only be guessed at. The surface of the Sun is far from homogeneous: when we talk about the distribution of the energy of solar light or about the temperature of the Sun, we always have in mind a rough, mean value. The apparent journey of the Sun across the sky is accompanied by a no less apparent change of energy distribution in its spectrum. At sunrise and sunset the Sun seems red, its rays having to penetrate a much thicker layer of atmosphere than when it is at the zenith.

The surface of the Sun almost always has spots on it, mainly in the equatorial regions (fig. 22). These spots are sometimes so large that they can easily be discerned by the eye through a smoked glass. One of the entries in the Chinese chronicles that have come down to us shows that sun spots were observed by the naked eye as far back as 28 B.C. In 1858 there was a spot visible on the Sun's disk 230,000 km. long, i.e., 18 times as long as the diameter of the Earth. The spot took up 1/36 of the total visible surface of the Sun. The spots are of various shapes with dark umbrae in their centres and less dark penumbrae on their outsides (fig. 23).

Spectroscopic investigation shows that the chief components in the region of the spots are hydrogen and calcium vapours. Gigantic whirlwinds, cyclones, consisting sometimes of streams of electrically charged particles, envelop the spots. The resulting electric currents are accompanied by enormous magnetic fields which cause

changes in the spectral lines (splitting them). These spectral changes make it possible to disclose the solar whirlwinds.

The number of spots on the Sun changes periodically, the length of one cycle being about 11 years. The curve in fig. 24 proves this periodicity. The years are

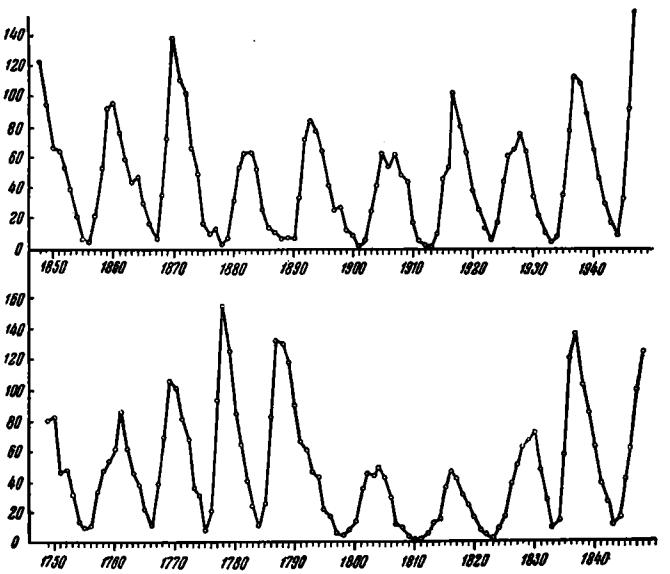

Fig. 24. Eleven-year sun-spot cycle

marked off along the horizontal axis, and the relative number of spots—along the vertical axis. The curve embraces a very large period of almost two centuries, from 1749 to 1947, and makes the periodicity quite obvious. This is, without doubt, a law of solar action which plays a very important part in the life of the Earth. Part of the same curve, from 1836 to 1926, is repeated in fig. 25 (lower curve), in the same co-ordinate system as the curve of magnetic disturbances on the Earth for the

same period. The parallelism of the curves is quite manifest. Thus, there exist other intermediaries besides gravitation and light between the Earth and the Sun. It is known now that streams of negatively charged particles—electrons—are constantly flowing from the Sun to the Earth. These streams of electricity are deflected by the magnetic poles of the Earth toward the polar regions and cause magnetic changes on Earth, as

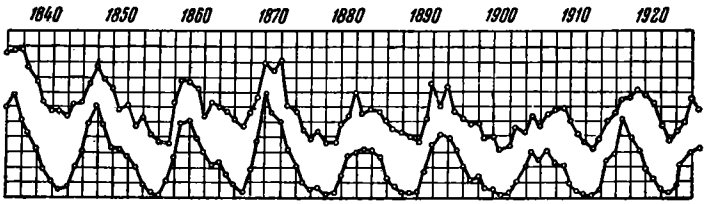

Fig. 25. Periodicity of sun-spots and parallelism between the number of spots and the magnetic disturbances on Earth, (upper curve)

recorded in fig. 25. On the other hand, penetrating into the upper rarified layers of the Earth's atmosphere, these fast electrons make the gases in those layers emit light. This is the explanation of the northern and southern lights. The frequency of occurrence of the aurora in the polar regions shows the same periodicity as the sun-spots and the magnetic disturbances on Earth.

Changes in the number of sun-spots have a substantial influence over changes of weather, and, hence, over the vegetation and all forms of life on the Earth. Fig. 26 is a photograph of the cross-section of a pine-tree trunk, showing how the thickness of the annual rings changes in clear-cut periods of eleven years each, corresponding to the sun-spot cycles. In fig. 27 the sun-spot curve for the period 1830-1910 is compared with the mean curve of tree growth for several European countries. The parallelism is quite clear in this case also, although the pic-

ture is somewhat complicated owing to the influence of other factors independent of the sun-spots. Thus, there is no doubt that sun-spots are an important factor in the life of the Earth's surface.

The outer shell, the only part of the Sun we can see under usual conditions, is called the photosphere. This

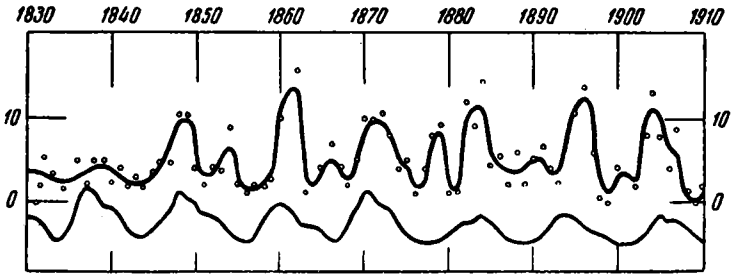

Fig. 27. Comparison of the sun-spot curve with the mean curve of tree growth for several European countries (upper curve)

shell presents a grained structure, which becomes especially obvious if the solar disk is photographed in the monochromatic light of a single spectral line, say, that of hydrogen or calcium (fig. 28). The granules, of different shapes and sizes, evidently correspond to clouds of vapours and gases floating in the photosphere. Ordinary clouds on Earth are found to have a similar grained structure, if viewed from above, from the top of a mountain (fig. 29). Some parts of the photosphere, called faculae, are especially bright; the calcium lines are the strongest in these places.

During full eclipses of the Sun we have an opportunity of seeing the solar shell in its details—we see it as if in cross-section (fig. 30). The photosphere is surrounded by a thin layer of a red colour, called the chromosphere, into which the faculae from the photosphere penetrate. The depth of the chromosphere is about 10,000 km. Colossal fountains of luminous gases, called

Fig. 23 Section through the trunk of a pine-tree, showing how the thickness of the rings varies in eleven-year periods

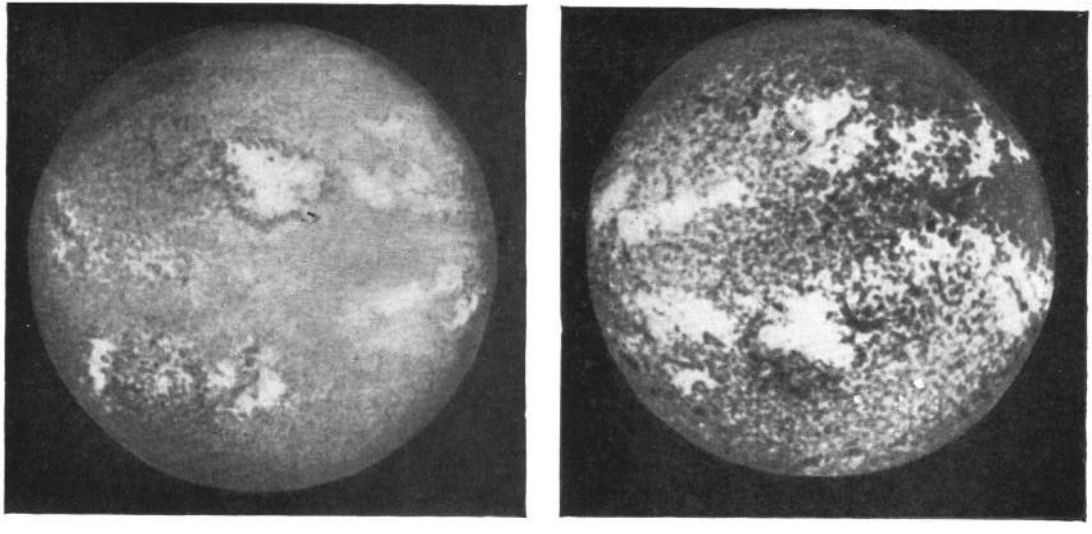

Fig. 28 Spectrogram of the Sun, taken in the light of calcium (A) and hydrogen (B) lines

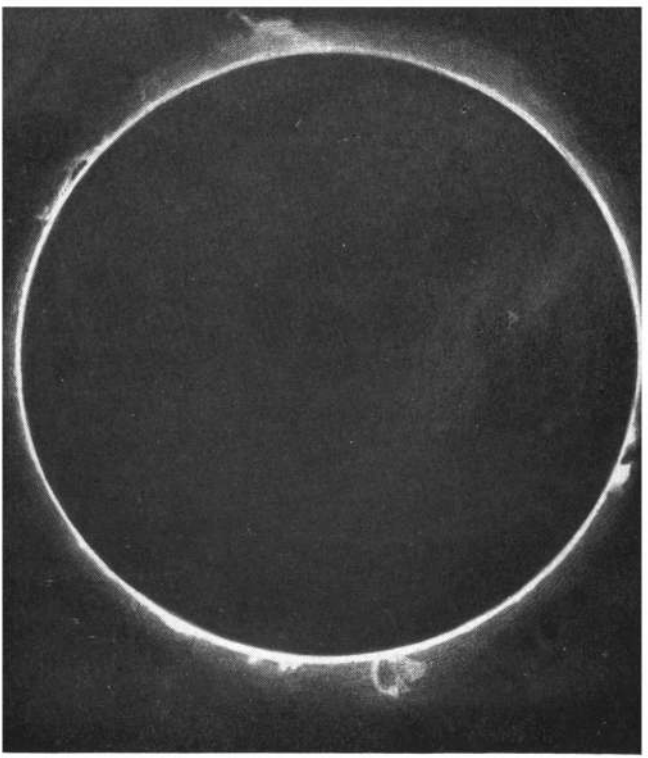

Fig. 30 View of Sun's chromosphere, showing prominences

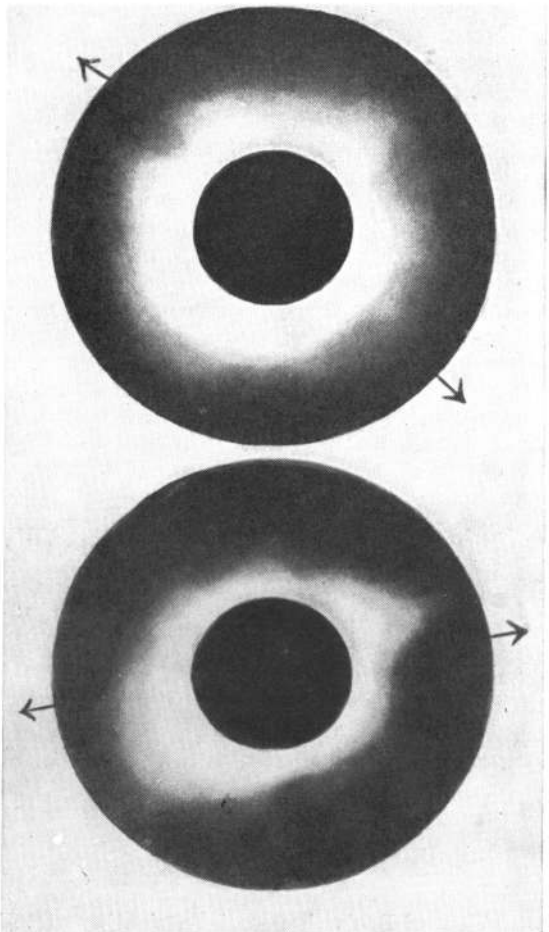

Fig. 31 Photographs of solar corona taken during total solar eclipse of September, 1937. The photographs were taken through a polaroid in two mutually perpendicular positions, as shown on the photographs. The different shapes of the photographs show that the light of the corona is polarized

prominences, rise out of this layer, sometimes attaining a height of several hundreds of thousands of kilometres. There are two main types of prominences, the sun-spot type and the eruptive type. In the first, the chief source of light is hydrogen, like in the chromosphere; the second contains well-defined metallic vapour lines besides the

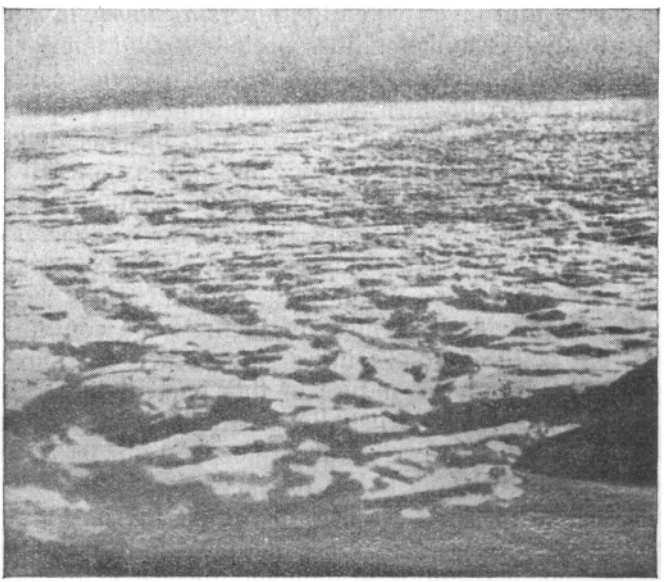

Fig. 29. View of clouds from the peak of a high mountain

hydrogen. Lately astronomers have found new convenient methods of observing prominences at any time, not only during eclipses. This is done by carefully blotting out the Sun's disk in the telescope by means of a dark opaque disk and using absolutely flawless glass (containing no dispersing bubbles or knots) and high-quality light filters, which let through only a narrow section of the spectrum. Besides, in the course of the last decade highly

perfect light filters have been developed in the U.S.S.R. and abroad, which transmit practically only one narrow spectral line. As a result of this it has become possible to take motion pictures of the prominences, disclosing peculiarities of the solar eruptions which had formerly been absolutely indiscernible.

Between the photosphere and the chromosphere there lies a very thin layer called the *reversing layer*, in which the principal Fraunhofer lines probably originate.

A striking phenomenon called the *corona* can be observed even without a telescope during full eclipses of the Sun. The corona (fig. 31) extends millions of kilometres beyond the edge of the Sun, and is generally of a radial structure. Sometimes the rays surround the solar disk approximately uniformly all around, in other cases the corona is especially elongated in certain directions. Three spectra can be distinguished in the cross-section of the corona. The brightest of them is the continuous spectrum of the corona's inner ring, which contains no Fraunhofer lines; the nature of this part of the corona is still a puzzle. It is usually attributed to the dispersion of the Sun's rays in an atmosphere of electrons. However, up till now it has not been found possible to develop this idea consistently to completion in conformity with all the facts. The second spectrum is also continuous, but it contains Fraunhofer lines; it is attributed to the reflected light of the photosphere (the reflection being caused, possibly, by comparatively cool dust particles at some distance from the Sun). The third spectrum is linear, and corresponds to the luminosity of atoms. It may be considered that the third spectrum appears as a result of the fluorescence of vapours under the influence of solar light. This is suggested by certain peculiarities of the polarization of the spectrum. Thus, the Sun is surrounded by a layer several million kilometres thick of substance in a rarified state, partly in the form of vapours, partly in the form of dust. These vapours

and dust may be repelled from the Sun by electrical forces and the pressure of light. In many respects, however, the solar corona is still a recondite phenomenon. There is a possibility, for instance, that the luminosity of the corona is partly due to a kind of "self-dispersion" of the rays as a result of intensive light beams intersecting in the vicinity of the Sun. The present-day theory of light takes such a possibility into account.

We shall finish our brief and greatly simplified description of the phenomena taking place on the Sun's surface with a few words about the energy radiated by the Sun. This energy is distributed throughout the whole spectrum in both its visible and invisible regions, about 40 per cent of the total energy being in the visible range.

Let us assume that the Earth has no atmosphere. On the basis of direct measurements of the energy of the Sun's rays that actually fall on the Earth's surface, and taking into account the influence of the atmosphere, we find that if there were no atmosphere, sheerly falling solar rays would bring each square centimetre of the Earth's surface an average of 2 small calories per minute or 0.033 small calories per second. In reality, part of the energy is absorbed by the atmosphere.

Knowing this figure, the so-called *solar constant*, we can easily calculate the total energy radiated by the Sun per second. To do this it is necessary only to make the natural assumption that the Sun radiates energy uniformly in all directions, to find the surface of a sphere with a radius of 150,000,000 kilometres (the distance between the Sun and the Earth) and multiply this area, expressed in square centimetres, by the solar constant, i.e., by 0.033 small calories. The result is approximately 10^{26} small calories per second (i.e., a figure consisting of a 1, followed by 26 zeroes). This figure in itself is not very graphical, nor is the idea of the calory very concrete. It will therefore be instructive to perform the following calculation.

Modern physics has found that energy is always equivalent to mass. The first and most important indication of this bond was the fact that light exerts pressure on bodies. This fact was discovered by P. N. Lebedyev, who measured its magnitude. His refined and extremely difficult experiments proved that light falling on a blackened plate which completely absorbs it exerts a thrust on the plate equal to E/c, where E is the luminous energy absorbed per second and c the velocity of light. If the plate is not black, but mirror-like, so that it completely reflects the incident light, the pressure is twice as high. After many years of research Lebedyev proved, further, that light exerts pressure not only on solids, but on gases as well. This is a fact of primary importance for the present-day theory of solar phenomena.

From the laws of mechanics it follows that to stop a flow of any kind (water, light) which exerts pressure, in a length of time t, this flow has to be "neutralized" by a force F, which can be determined from the equation $Ft=mv$, where mv is the product of the mass m the flow conveys, by its velocity v, this product being called the momentum. Thus, the thrust of the flow F equals the change of momentum per second, i.e., $F=\frac{mv}{t}$. In the case of a luminous flow $v=c$ (the velocity of light). Equating the deduced expression for the thrust to the expression for the magnitude of the light thrust found in Lebedyev's experiments, we get $\frac{mc}{t}=\frac{E}{tc}$, whence $m=\frac{E}{c^2}$. *)

The above formula determines the mass of light m, equivalent to its energy E. This extremely important equation was deduced here by applying the laws of mechanics to Lebedyev's optical measurements. At first

* The deduction given here is somewhat different from that of S. I. Vavilov, in which the same magnitude is used to denote both luminous energy and luminous power. This might have led to difficulties for the reader.—*Ed.*

sight, its application is restricted, therefore, to the field of light. Einstein was the first to show that the equation

$$mc^2=E$$

is universal and should hold true for all forms of energy. With the progress of modern physics, especially that of the atom and the atomic nucleus, experiment confirms Einstein's conclusion more and more extensively, and at present it should be regarded as one of the most important relationships in all science.

Applying this formula, let us compute the mass represented by the energy radiated by the Sun per second. The figure 10^{26} small calories per second calculated above will be found to be equivalent to about *5 million tons per second.* This mass, tremendous as it is in itself, is infinitesimal compared to that of the Sun. We found above (p. 69) that if the Sun emitted a 1,000 million tons per second it would take it 30,000 million years to decrease its mass to one-half of its present value. As it is, with the Sun losing only 5 million tons per second, it will take it 6,000,000 million years to reduce that much.

In exactly the same manner the energy received per second by the entire surface of the Earth can be computed as mass. It must be kept in mind that only half of the globe is illuminated at a time, and besides, that the solar constant refers to sheer rays. This computation results in quite a modest and easily remembered figure—about 2 kilograms per second.

These calculations, which have made the amount of energy radiated by the Sun somewhat easier to grasp, are at the same time of considerable importance. We are awed by the mass of the Sun and by its practically inexhaustible energy. How are masses like that of the Sun accumulated, and where is the source of their continuously radiating energy? Masses are probably attracted to solar centres by universal gravitation. But apparently the mass of the Sun is almost the outside limit; there are

accumulations of matter about ten times as large as the Sun, but further growth is unknown to astronomers. What is the reason for this limit?

Accumulation of masses under the influence of universal gravitation results in the development inside the luminaries of enormous pressures and immense temperatures, which must reach tens of millions of degrees. Brought far beyond white heat, to the heat of X-ray light, the inside of the star emits an exceedingly large amount of radiant energy, which travels from the core outward. This internal light presses outward on the star's mass. Thus, the action of gravitation is countered by the pressure of the light. Of course, this reaction cannot exceed the gravitation that brings it forth. But the pressure of the light is supplemented by the centrifugal force which arises due to the rotation of the star. When the sum of the light pressure and the centrifugal force becomes equal to the force of gravitation, further increase of the mass of the luminary must stop. Theoretical calculations show that, indeed, a mass of the order of the Sun's must be the outside limit in the universe. Such is the partial explanation astrophysics can give concerning the origin of the Sun's mass.

But how is the energy lost by the Sun in the form of radiations replaced? At one time it was thought that the required compensation could be supplied by the flow of meteors falling on the Sun and amounting to about one-hundredth of the Earth's mass per year. It was pointed out also that contraction of the Sun's diameter to an extent of 75 m. per year should develop enough heat to equal that radiated. In such a way the existence of the Sun as it is today could be explained for a period of 100 million years. This period, however, is infinitesimal; geology and astrophysics demand a figure of at least tens of billions of years for the life of the Sun. Such a long life cannot be explained by the assumptions mentioned above.

The sources of the radiations of the Sun and the stars must be sought along entirely different lines—along the lines of the energy resources discovered by modern physics. The correlation between energy and mass we have just discussed shows in the most general form that any accumulation of mass may be considered as an equivalent of energy. Each gram of mass is an immense amount of energy, the magnitude of which can be calculated by multiplying the mass by the velocity of light squared. One gram of mass is equal to 20,000,000 million calories. To generate such an amount of energy 20 thousand tons of coal would have to be burned.

We have mentioned coal as a simple example of a source of thermal energy. It will be instructive to ponder over this example for a few moments. A lump of coal is an inert mass, very much the same, from a mechanical point of view, as a piece of stone. This lump lay in an inert state for hundreds of thousands of years, until it finally fell into the hands of man, who managed to transform the latent energy of the coal* into the available heat form by burning it in oxygen. This discovery was a very important event in the history of mankind. It meant, as we know now, the liberation of the latent chemical energy of coal. But the people of our day have witnessed another exceedingly important event in the history of mankind—the beginning of the era of mastery over atomic energy that will in its time give birth to a most important stage of modern engineering, making it possible to solve economic problems which have been beyond our means up till now.**

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* The author means, strictly, not the latent energy of the coal, but the energy of the system (coal + oxygen) liberated upon the transition of this system to carbon dioxide (combustion).—*Ed.*

** The world's first industrial atomic power station (5,000 kilowatts) was put into operation in the USSR in 1954. Soviet scientists are now working on projects of industrial atomic stations with capacities of 50-100 thousand kilowatts.—*Ed.*

The energy of atomic nucleus, unleashed in the proper processes, is immeasurably greater than the energy of the combustion of coal. Still, in both cases we have to do with examples of essentially the same thing—utilization of the energy latent in matter in an available from.

By what methods can the latent energy equivalent to mass be transmuted to the available forms of luminous or thermal energy? According to the conceptions of modern physics three such methods can be indicated. The first is complete transformation of the particles of substance, e.g., protons, into light. In the previous chapter (p. 52) we discussed the transformation of light into substance, the transition of a light quantum into a positron and an electron. The inverse process, however, is also possible. Its probability under ordinary conditions is exceedingly small, but inside the Sun, where the density and pressure are enormous, and the temperature reaches millions of degrees, such processes may take place much more often. As a result of these processes the entire mass of the particles which disappear manifests itself in the form of luminous energy. In order to evade a common error, it should be noted here that the mass does not disappear, and does not change to energy, as is sometimes stated; the mass remains in the form of the mass of the photons produced, and only the equivalent energy is converted from its latent form into the available form of luminous energy.

The second method of transmutation of the latent energy equivalent to the mass into available energy is by the disintegration of atomic nuclei. An old, well-known example is the disintegration of the radium atom. However, this process occurs very rarely in nature and cannot serve as a source of any considerable quantities of energy. An important step forward in the utilization of nuclear disintegration as a source of energy was the discovery of the fission of uranium 235 under the action of slow neutrons. This uranium isotope (235 is its atomic

weight) constitutes 0.7 per cent of ordinary uranium. The chief advantage of the process is that it is of a chain nature. Each nuclear fission gives rise to new neutrons, which can cause fission in their turn, etc. We get a chain of disintegrating nuclei, each link of which is accompanied by the generation of considerable amounts of energy. This phenomenon forms the basis of the entire present-day technique of atomic energy liberation. However, the process just mentioned is evidently of no importance for the Sun, since, according to very plausible theoretical considerations, heavy atoms, such as uranium and others, do not exist inside the Sun.

There is, however, a third way of converting the latent energy inseparably bound up with mass into available forms, which is the opposite of the second; it consists not in the disintegration, but the complication, the synthesis of atomic nuclei. This has been known for a long time from comparison of atomic weights. For instance, the atomic weight of hydrogen is 1.0080, and that of helium—4.003. But since helium is built up of four hydrogen atoms, we should expect its atomic weight to be $4 \times 1.0080 = 4.032$. The difference, $4.032 - 4.003 = 0.029$, is quite tangible.* The only explanation for this difference is that the formation of the helium nucleus from hydrogen nuclei is accompanied by the transformation of a considerable amount of substance mass into the mass of radiations or other forms of energy. This energy is enormous: the transmutation of one gram of hydrogen into helium generates 5 million times more energy than the same gram of hydrogen when burned in the presence of 8 grams of oxygen to form water.

There are quite weighty grounds to assume that the formation of helium nuclei from hydrogen nuclei (pro-

* To be more precise, the helium nucleus is built up of two protons (hydrogen nuclei) and two neutrons. If this is taken into consideration, the difference between the atomic weight of *He* and the particles it is composed of becomes 0.030.—*Ed.*

tons) is the process that forms the basis of solar energetics. The accelerator or "catalyst" in this process is probably the carbon nucleus. Whether this is really the process that causes the transformation of the energy bound up in the atomic nucleus into the radiations within the Sun, is still, however, a question; it is only known for certain that there are several possibilities of this being so. There is no doubt that the solar light we receive on Earth is the result of the work of a colossal machine, which has been liberating atomic energy within the Sun for many billions of years.

We cannot in our earthly laboratories reproduce the immense pressures and temperatures that must exist within the Sun. One thing is beyond doubt, however—that radiation leads to a constant decrease of solar mass. The Sun, so to say, is burning itself out, but not in the usual chemical sense, inferring that the products of combustion remain as useless inert mass; in this case mass passes into universal space in the form of active energy—luminous radiations; the mass of two litres of water is equal, as we have seen, to the mass of all the light received per second from the Sun by the whole Earth. But we know well that the whole Earth lives on the two kilograms of light, while two litres of water are an imperceptible "triviality."

Solar rays bring with them solar mass. Light is not an immaterial messenger from the Sun, but the Sun itself, a part of it, which comes to us in a perfect, energetically available form, in the form of light.

THE EYE*

> **The eye owes its existence to light. From among the indifferent auxiliary organs of animals light calls forth an organ, which would become like unto itself; and thus is the eye born in light, for light, in order that the inner light meet the outer.**
>
> **GOETHE**

> Thy rays create the eyes of all thy creatures.
>
> LESSER HYMN TO ATON

The living creature possesses no more faithful and powerful defender than the eye. To see—means to distinguish friend and foe and all the details of one's surroundings. The other sensory organs fulfil the same duty, but much more roughly and feebly. The sense of touch and the feeling of warmth supply us with information of the external world only upon immediate contact; hearing and smell, which bring news from afar, give us an insufficient idea of distance, direction and shape. The present-day physicist convinces others of the reality of atoms by alluding to the fact that we have finally suc-

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* Some very slight changes have been made in this chapter, in accordance with the terminology of physiological optics. S. I. Vavilov sometimes makes digressions from the precise terminology accepted in the science of light. These digressions may have been made on purpose, owing to the complexity of the terminology, which renders it of little use in popular exposition. For this reason, in such cases we have restricted ourselves to a correction of errors and misprints.—*Ed.*

ceeded in seeing the paths of individual atoms, while the former opponents of the existence of atoms constantly argued that nobody had ever seen them. This is the sense of Anaxogoras' saying: "Vision is the appearance of the invisible"; the invisible world becomes a reality through vision.

The tasks to be performed by the ideal eye as a physical instrument are quite obvious. The surrounding objects emit light. The eye gets the direction of the rays, their energy, spectral composition and polarization. A separate, individual sensation must be received from each point of the object. Ideally, all these sensations combined in the cerebral centre should reproduce an exact copy of the radiating surface with all its optical peculiarities. Spatial correctness of the message is the important thing; the brain has to receive correct information as to shape, dimensions and distances. After this the brain can make adjustments in the information received, depending on the requirements of the organism.

As we shall see, the eye comes quite close to the fulfilment of this ideal task.

But how did it originate, this auxiliary live organ capable of coping with optical difficulties sometimes more perfectly than the modern optician, in spite of the immense physical knowledge and technique he has at his disposal?

The answer to quesitons of this kind was given by Darwin's theory of evolution in biology. The eye is the result of an exceedingly long process of "natural selection," the result of changes that have taken place in the organism under the influence of the environment and the struggle for existence, for better adaption to the external world.

The mighty factor of heredity guarantees the retention of biological properties if they correspond to the external conditions and increase the vitality of the organism in its struggle for life. The diversity of the influence

of the environment gives rise to the differences in separate individuals, which in some cases afford them advantages over the others. This is how "natural selection" occurs, by virtue of which only the strongest, the best adapted to the external conditions, survive.

In the infinite diversity of living forms around us we find all kinds of different solutions of this optical problem; none of them are perfect, but they all have much that is rational and, from the point of view of man, "clever."

Fig. 32 gives some examples of various solutions of the optic problem, various "designs" of "instruments" for the visual perception of the external world. In fig. 32, A is an example of an "eye" in a single-cell organism, consisting of a spherical lens *l* situated in front of a sensitive substance. Of course, this organ cannot be regarded as an apparatus for producing images. The infinitesimal dimensions of the lens and the retina result in acute diffraction phenomena which greatly distort the image. In the same figure, B shows the optic organs of the dew worm. This creature has no eyes, but the entire surface of its body is sensitive to light; optic cells ("eye specks"), connected to nerve fibres, are distributed uniformly all over its body, so that images are out of the question. Fig. 32, C, is a primitive solution of the optic problem, light being perceived by an optic depression, something like an ear; this device enables its owner to determine approximately the direction of the luminous body, but no more. In fig. 32, D, we see a more advanced solution of the problem—a live camera obscura with a tiny aperture *p* and an internal light-sensitive cavity *r*; such are the optic organs of shell-fish. The last four examples in fig. 32, E, F, G, and H, are successive stages of perfection of optic organs with lenses. At first, with the scorpion, it is but a very rough instrument: the lens is a sphere set up close to the sensitive layer *r*. It resembles the glass spheres used by the ancients, according

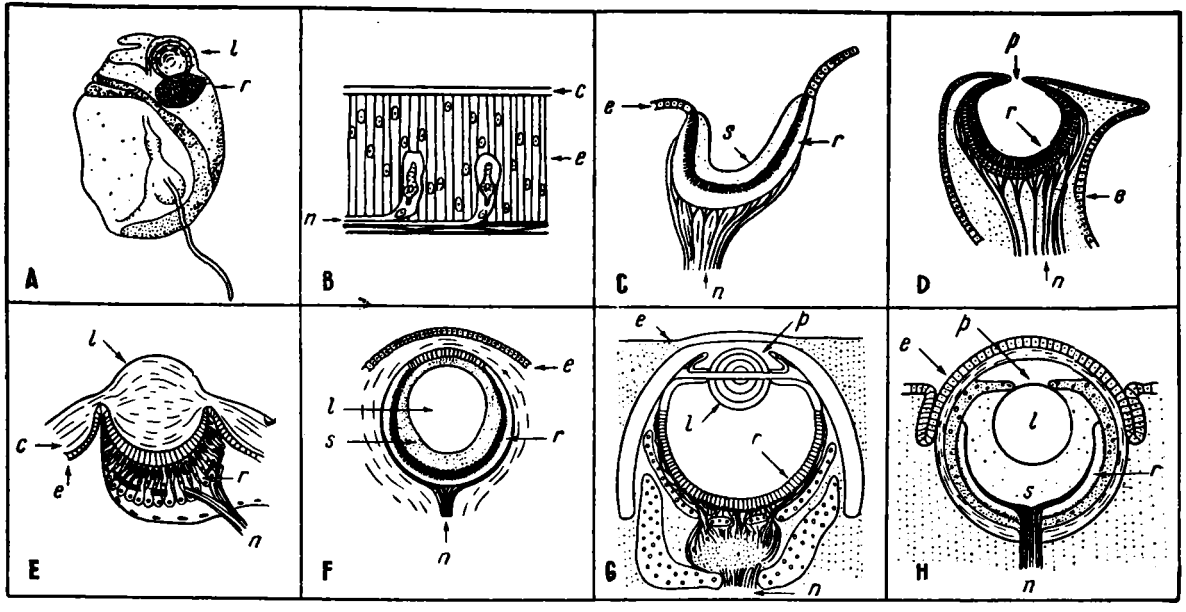
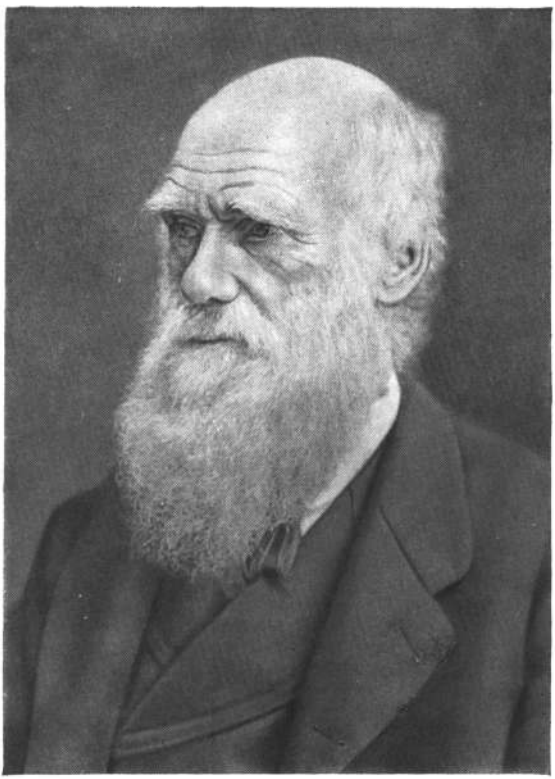


Fig. 32. Different methods of visual perception in the animal world: A—a single-cell organism, the *Pouchetia cornuta*; B—eye specks distributed all over the skin of the dew worm; C—optic organ in the shape of a depression, *Patella bivalve*; D—eye in the form of a camera obscura, mollusc; E—eye of the scorpion *Euscorpine* with a concentrating lens; F—eye of the *Murex* snail; G—image-producing eye of the Cephalopod *Loliga*; H—eye of a vertebrate; c—cuticle; e—epithelium; I—lens; n—nerve fibres; p—pupil; r—retina; s—inner transparent medium



Charles Darwin (1809—1882)

to legends, as burning glasses, or the Leuwenhoek microscope, in which drops of honey were used as "lenses." Fig. 32, F, G, and H, show the gradual development of the eye through the snail and the cephalopod to that of

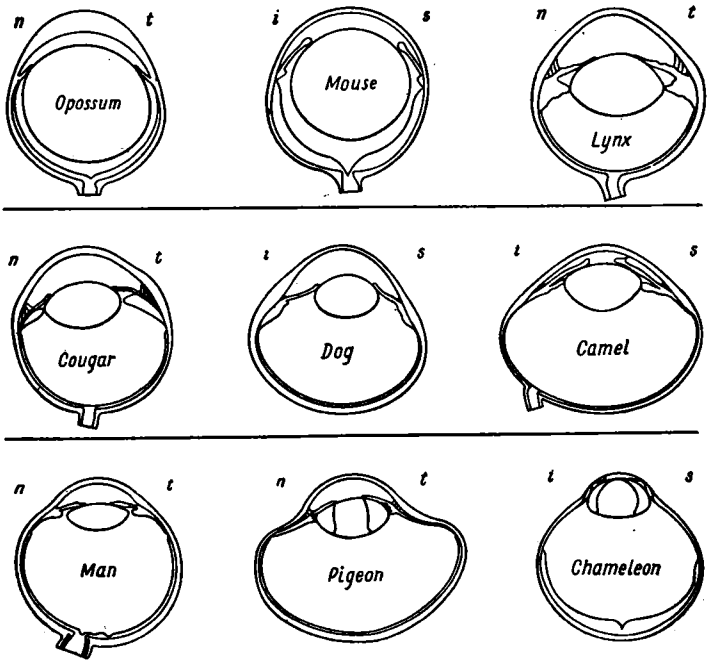


Fig. 33. Eye of various vertebrates in cross-section

vertebrates which resembles the human eye. Fig. 33 shows the eyes of several vertebrates in cross-section, including nocturnal (opossum, mouse, lynx) and diurnal (cougar, dog, camel, man, pigeon, chameleon) animals. Without commentary it can be seen that the problem is solved optically in a great variety of ways.

The peculiarities of the eyes of deep-water fish, living at depths to which the light of the Sun hardly ever

penetrates, are very interesting and instructive as an example of the adaption of live organisms to their environment. It would seem that at great depths fish should be without eyes altogether, since they are of little use there. But this is not the case. Most deep-water fish have eyes, and, moreover, the largest (relatively) in the world of vertebrates. Furthermore, their eyes are, evidently, the most sensitive in the animal world. How is this fact to be reconciled with the absence of light at such depths? The answer is, primarily, that weak traces of sunlight do penetrate to a considerable depth into the sea. Secondly, the advantages of visual perception in seeking food, in reproduction and in the struggle for existence are so great that it is much more expedient to enhance the sensitivity of the eye to light than, following the "line of least resistance," to doom it to atrophy.

But the fact that creatures living in the depths of the sea have eyes is due not only to the penetration of feeble traces of light into those depths. Deep-water fish are themselves capable of producing light, thus illuminating their surroundings somewhat and becoming visible to other animals with a sense of seeing. For this purpose they develop luminous organs situated near the eyes or in other parts of their bodies. The *Photoblepharon palpebratus* and the *Anomalops katoptron*, shown in fig. 34, have luminous tissues (shaded with dots in the drawing) next to their eyes. These tissues glow as a result of oxidation and serve as "headlights" for the fish, illuminating its way and the things it comes across. But these "headlights" may prove dangerous for their possessors, since they make the latter visible to their enemies. For this reason, both species of fish shown in the figure have eyelid-like devices for shutting off the luminous headlights when necessary. The first fish named does this by moving out a special dark fold of skin, while the second can draw its luminous tissue into a special protective

pocket (fig. 34, *c*). "Luminescent lamps" are not by any means a rarity with deep-water fish. More than 90 per cent of them possess such organs.

In the subsequent pages we shall have to do mostly with the human eye. This follows from the main subject

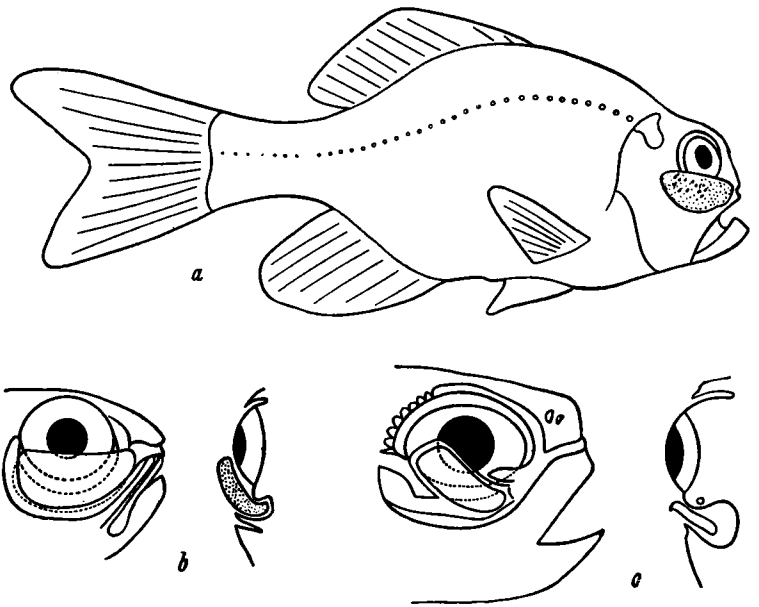


Fig. 34. Fishes with luminous organs connected to their eyes. *a—Photoblepharon palpebratus*; *b*—its head in profile and cross-section, showing the luminous organ and the screen covering it; *c*—head of the *Anomalops katoptron* in profile and cross-section. The light-producing device and the cavity in which it is concealed can be seen

of our book, which is the connection between the eye and the Sun; besides, only the human eye has been studied in detail, though there is still a great deal unknown about it to this day.

Let us begin with the problem of space. How is geometrical similarity attained by the eye, and how does it estimate distance? Light brings with it only one element of space, the direction of its rays, which must be utilized by the light-sensitive organ. To the green leaf light is not only a messenger from the objects surrounding it, but its source of life as well. The leaf reaches out towards the Sun, and the solar rays direct it. Leaves grow more on the sunny side, and arrange themselves on the tree in such a way as not to shade one another from the Sun. A great many plants and flowers turn on their stems, following the movement of the Sun during the day. Sunflowers planted on large areas follow the position of the Sun in unison, as if in response to a command. The same turning towards light, phototropism (sometimes negative) can be observed with many kinds of microbes, infusoria and other very simple organisms, besides plants. This reaction to light, to the direction of its rays and energy may be regarded as a primitive form of vision.

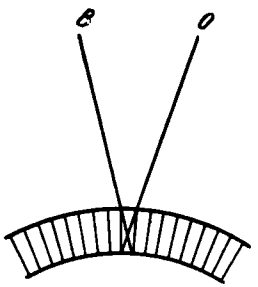


Fig. 35. Diagram of the eye of certain insects

Some insects have devices like that shown in fig. 35 for determining the direction of the rays and producing visual images. Tiny cones are arranged in mosaic fashion (like a honeycomb) on a retina made of nerve ends. The walls of these cones are coated with a dark-coloured substance which absorbs light like the dull black varnish on the inside of a telescope. Only the rays within the boundaries of the lines *B* and *O* can penetrate to the bottom of one such conical cell. The rays which fall on the bottom of any other cell will be of a different sector. As a result, the retina receives a rough mosaic image

of the object, from which the insect can discern its shape.

Just as in the case of the photographic camera man gradually passed from the camera obscura to the camera with the objective lens, so also did biological evolution lead from the mosaic of tubes to the optic apparatuses with lenses we find in vertebrate animals. The cross-

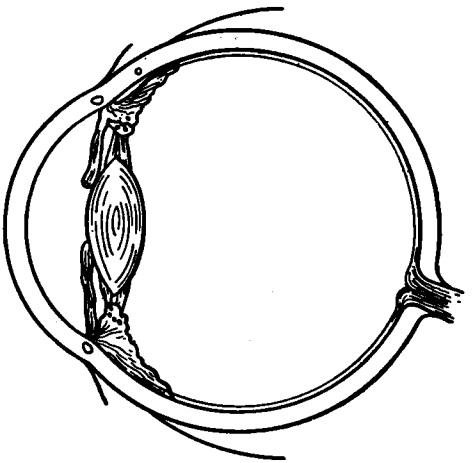


Fig. 36. Cross-section through the human eye

section of the human eye is shown in fig. 36. The eye is almost spherical, its diameter being about 16 mm. for a new-born child, and about 24mm. for an adult; the diameter of a horse's eye-ball may be up to 51mm., and that of a rat—6mm. On the outside the eye is enclosed in a thick white coat (the sclerotic); the front part of this coat is transparent and convex (the cornea), its thickness being about 0.5 mm. Behind the cornea is the anterior chamber of the eye, separated from the posterior chamber by a crystalline lens. Directly in front of the lens is the iris with an almost circular aperture which

limits the cross-section of the light beam entering the eye. The thickness of the anterior chamber and the crystalline lens is about 3.6 mm. The anterior chamber is filled with a transparent liquid, and the posterior, with a transparent vitreous body; the index of refraction of both is close to that of water (1.336). The inside surface of the sclerotic is lined with a vascular membrane which may be regarded as a ramification of the blood vessels feeding the eye. On the inner surface of the vascular membrane (the chloroid coat) is the light-sensitive retina. It consists of two layers, the outer or pigmented layer, and the inner or neural layer, and is a ramification of the optic nerve.

The transparent crystalline lens is lamellar in structure. The convexity of the lens can be varied by means of muscles on the iris; the highest index of refraction in the layers of the lens is 1.41. The image is produced on the retina of the eye in the same way as on the photographic plate of a camera. The faculty of changing the convexity of the crystalline lens (accommodation) permits the eye to focus so as to produce a distinct image on the retina. Children can see objects distinctly at a distance of 7-10 cm. from the eye. The normal eye of an adult sees objects distinctly at a distance not less than 14 cm. In old age the faculty of accommodation becomes much weaker.

Defects of the eye (short- and long-sightedness) can be corrected with the aid of artificial glass lenses—spectacles, diverging or converging. The image on the retina is far from perfectly correct. It is exact only if the image is not very large and lies on the eye's axis. It must be noted, however, that so-called spherical aberration is quite well corrected in the human eye. This is mainly due to the fact that the inside layers of the crystalline lens are of greater density than the outside layers.

The quality of the image improves when the inlet opening of the eye governed by the iris is contracted.

This can easily be checked by long-sighted persons. With strong illumination they can see objects clearly and distinctly at small distances (25-40 cm). As we know, under such conditions the pupil of the eye contracts, reducing the angle of opening for the rays passing into the eye. On the other hand, a long-sighted person can read comparatively small print at a short distance without spectacles if he looks through a tiny opening formed by clenching his hand and holding it to his eye.

These defects, however, are compensated to a certain extent by the possibility of easily turning the eye in its socket. The eye can turn through more than 80° vertically and horizontally, which enables it rapidly to take in all the points of any large object regarded.

The approximately plane figure on the retina gives an idea not only of the shape of the object, but of its dimensions and distance as well, even if only one eye is used. This may be due to our referring the one-eyed observation to previous observations in which we estimated distances and dimensions of objects around us using both eyes; previous experience and habit enables us to determine the distance and dimensions in this case. Doubtlessly, the accommodation of the crystalline lens is also of importance, since we unconsciously sense its tension and can thus estimate distance. Unconscious movements of the eye also play an essential part. We get a number of images of the object in a short space of time from different points of view, and estimate the distance by comparing them.

However, the reliability of the spatial impressions we get when using one eye is rather low. Take a pencil in each hand, close one eye and try to make the pencil-points touch. In most cases our first trial will be unsuccessful. On the other hand, using both eyes we will never fail in this experiment. In directing our eyes at a given object we set them at a definite angle (fig. 37), and the instinctive estimate of this angle serves as a measure

of distance for quite a wide range. It is very important to note that the subjective impressions and images we finally get are corrections of the direct physical image produced on the retina, these corrections being made automatically by our brain. One of the chief manifestations of this function of the brain is the straightening out of the images on the retina; in reality, these images, produced by the crystalline lens, are inverted. The corrective role of the brain in spatial perception is very

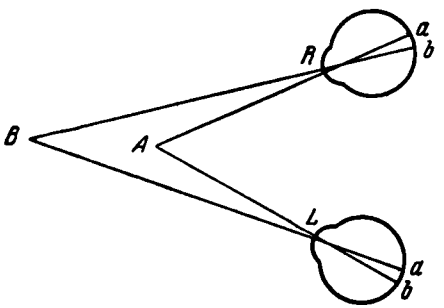


Fig. 37. Binocular vision

great. In the top half of fig. 38 we see the linear elements of the simplest graphical depiction of a cube; in the bottom half is the cube built up of these elements, and we immediately get the impression of space. This is, of course, a result of the brain's work, and forms the basis for the correct depiction of perspective in painting. In order to make an object seem farther away its dimensions on the painting have to be proportionately diminished. If one man is supposed to be standing twice as far away from the imaginary picture-viewer as another, he should be painted twice as small. The two men depicted will seem to us, nevertheless, to be of the same height, since this perspective size reduction only enables us to perceive the object at double the distance.

Fig. 39 gives the results of experiments by Gullway and Boring on the relation between the apparent size of an object and its distance from the observer. The object was a luminous disk, the angular dimensions of which remained constant, while the distance from the observer was varied from 3 to 36 m. Its apparent size was compared with that of another luminous disk stationed at a fixed distance of 3 m., the diameter of which could be

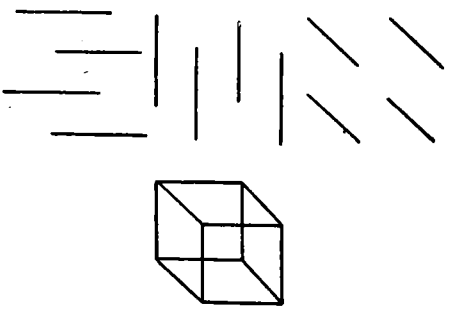


Fig. 38. Perception of perspective. The twelve lines at the top of the figure seem to be lying in the same plane. The cube made by moving them together parallelly is perceived as a space image

varied measurably to make it equal to the movable disk. If the brain did not make automatic corrections in the dimensions of the image on the retina, it might be expected that in fig. 39, where the distance in metres is computed along the abscissa axis and the perceived dimensions in centimetres along the ordinate axis, the result would be a straight line parallel to the X-axis (shown as a dotted line), since the angular dimensions of the first disk always remained the same. The actual results are entirely different. For all three cases of observation: with both eyes at once, with one eye, and through

On the horizon the Sun and the Moon seem very large, while at the zenith they are much smaller. This is also doubtlessly an optical error, common, moreover, to all human beings.* The cause of the error is not quite clear to this day. The following is one of the possible explanations. In estimating the luminosity of the sky we naturally and unconsciously accept as the boundary of the atmosphere the last part of it that sends a discern-

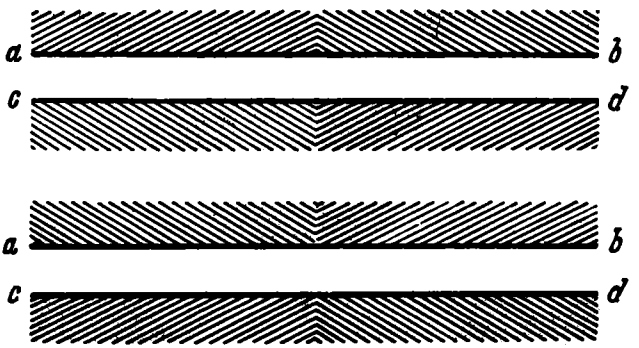


Fig. 41. Optical illusions

ible dispersed light to our eye, and we refer all objects in the sky to this limit. At sunrise and sunset the east or west edge of the atmosphere is the most luminous; the limits of the last part of the atmosphere which sends us light move much farther off, the sky becomes deeper, and we refer the luminary to this distant layer. Thus, we come to the same error as in the cases of the traffic sign and the cat, described above.

For psychological reasons errors are made not only in spatial images, but in plane figures as well. The two

* If the Sun or the Moon are photographed on the horizon and at the zenith they will be found to be of the same size in both positions.

pairs of parallel lines in fig. 41 seem bent and broken to us due to the shading around them. This illusion does not disappear even if we concentrate our attention, and the true state of the lines can be proved only by using a straight edge.

The drawing in fig. 42 is a regular square, but the shading over one of its angles results in a strong impression that the square is distorted. Broken, but strictly concentric circles have been drawn on a speckled back-

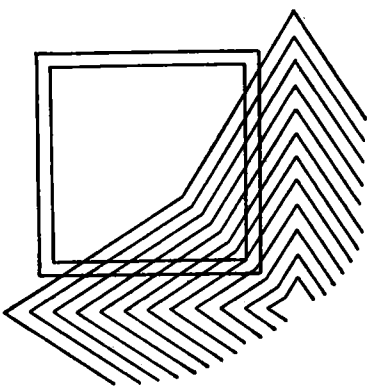


Fig. 42. Optical illusions

ground in fig. 43. The unavoidable impression, however, is that of a spiral. To prove that this is not so, we must use a pair of compasses. One of the reasons for these optical illusions is that the speckled shading makes our eye move involuntarily from line to line. If the drawings are illuminated by the instantaneous light of an electric spark, the illusions disappear (at least, in some cases): during the short time the spark is on, the eye does not get a chance to move perceptibly.

Thus, the solution of the spatial problem by the human eye and brain is far from perfect.

a narrow tube, the lines are inclined, the incline decreasing as more and more of the surrounding objects are eliminated from the field of vision.

The experiment just described corresponds quantitatively to the well-known fact that the dimensions of objects not far away do not seem to change even though they may be moving away from us. Only if the figures are very far off do we clearly notice that they have be-

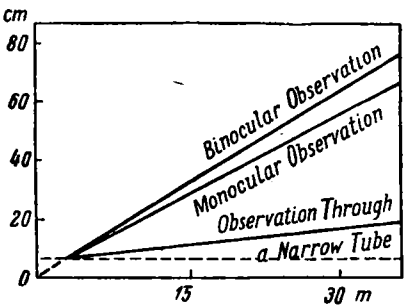


Fig. 39. Gullway and Boring's experiment

come smaller. This is easy to see if we look down from a high tower. The surroundings are of great importance as aids to the brain in making the corrections mentioned above in the physical image of objects on the retina. If the surroundings are eliminated, we begin to approach the purely physical result, as may be seen from the figure. Thus, the image perceived by the mind is not a simple physical image, but a modified one, corrected by the brain, without our being aware of the fact. This is, of course, of great biological importance. Living creatures need correct ideas of the objects surrounding them, rather than correct optical images. Fig. 40 is the photograph of a boy in a prone position, taken at close quarters. Optically everything is correct, but the snapshot seems to us an absurd caricature, the soles and hobnails being the main objects in the picture. Of course, this

snapshot testifies to the inexperience (real or feigned) of the photographer, but optically it is correct. If the brain did not make corrections in the work of the eyes, we should always be haunted by such caricatures.

But the corrections made by the brain may lead to errors and optical illusions. The author of this book has

Fig. 40. This picture of a boy in a prone position is an example of the discrepancy between optical and mental images

on many occasions been subject to gross spatial errors. Once a small red tin traffic sign hanging nearby from the trolley lines was taken for a red flag of an immense size because it was mentally erroneously associated with the spire of a distant building at the end of the street. On another occasion for a short moment a cat, apparently the size of a cow, was seen walking along a far-off fence; in reality, it was stalking over a roof close to the window through which it was observed. The error made in estimating the distance was about twentyfold.

Now, let us pass over to how the eye estimates the energy and the spectral composition of light. For this purpose it will be necessary to look into the structure of the retina, which makes this estimation. Fig. 44 is a

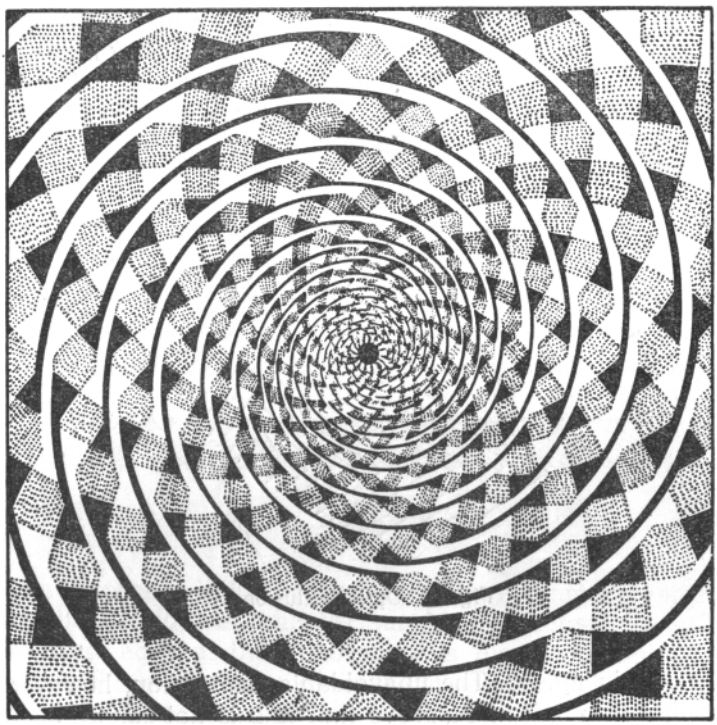


Fig. 43. Optical illusions

schematic cross-section of the retina. The outer layer *1*, next to the vascular membrane, consists of pigment cells. Next come the principal elements of visual perception *2*, called *rods* and *cones* for their shape. Layers *3-5* consist of nerve fibres running out to the rods and cones. Below

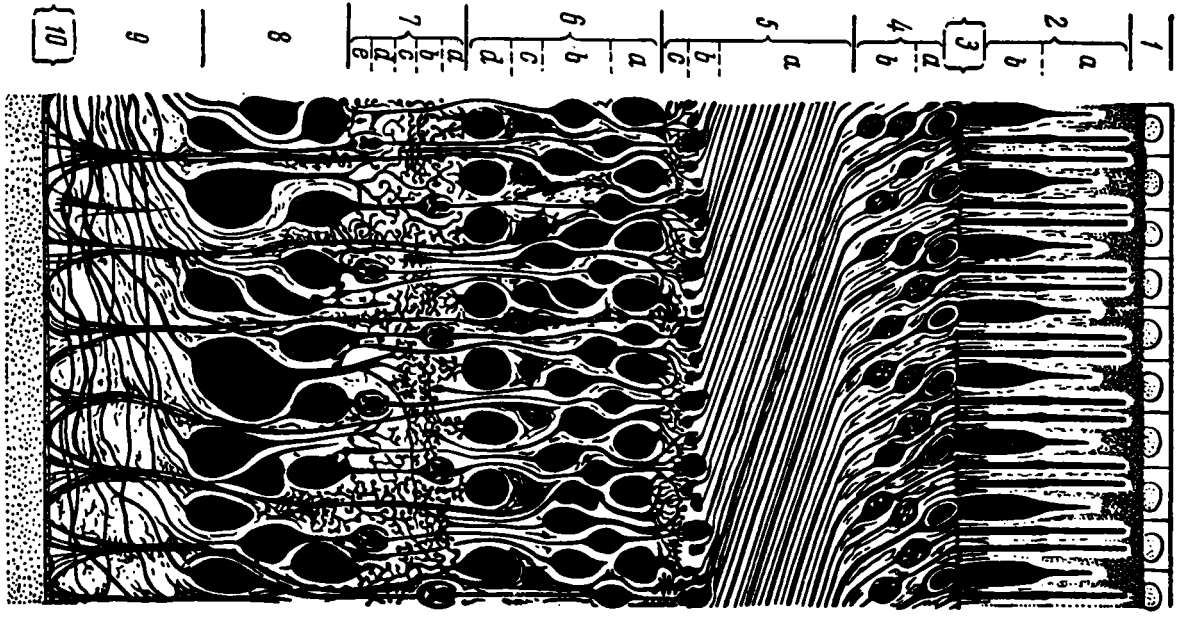


Fig. 44. Diagrammatic cross-section through the retina of the human eye

these are the so-called molecular layers, also connected by nerve fibres; *8* is the ganglionic layer, each cell of which is connected to a nerve fibre of layer *9*. Layer *10* is the inner limiting membrane. Each nerve fibre ends either in a cone or a group of rods. The mosaic of these cells on the surface of the retina is not at all uniform. The number of cones and rods is very large (about 7 million cones and over 100 million rods). Fig. 45 shows the

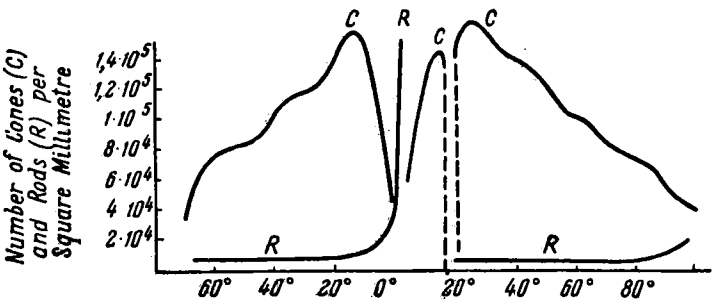


Fig. 45. Distribution of rods and cones over the retina, after Osterberg

distribution of cones and rods over the bottom of the eye. The abscissae are the angular distances from the "central depression" (fovea centralis) and the ordinates are the numbers of cones *C* and rods *R* per square millimetre. The curves are interrupted at the "blind spot," which we shall discuss below. The diagram shows that the cones predominate in the centre of the retina, and the rods—toward the edges. The rods are coloured with red visual purple which fades rapidly under the action of light. The length of the rods is about 0.06 mm., and that of the cones—about 0.035 mm. The rods have a diameter of about 2 μ, and the cones—about 6 μ. In the centre of the retina is the so-called "yellow spot" which

is oval in shape (maximum length 2 mm., minimum length 0.8 mm.). Cones predominate in the centre of this spot; the rods disappear entirely in the "central depression"; this is the point of clearest and most distinct vision. Some parts of the retina have neither cones nor rods. If we close our left eye and fix the right on the cross in fig. 46, the black circle on the right will become invisible when the page is moved to about 20 cm. from the eye; its image will fall on the point where the optic nerve enters the retina, which has no light-sensitive elements (the blind spot).

Fig. 46. Mariotte's drawing for finding the blind spot

The perception mechanism of the eye is as complex as its optical part is simple. Not only do we not know the physiological sense of the separate elements of the retina, but we are not even able to tell how rational the distribution of the light-sensitive cells over the retina is, what the blind spot is for, etc. This is no artificial physical instrument, but a live organ in which merits are interlaced with shortcomings, but everything is inseparably combined into a living whole.

Now let us estimate the energy of the light that comes to the eye. This problem is difficult to separate from that of chromaticity; the eye receives visual impressions only from rays with wave-lengths from about 400 to 750 mμ. Ultra-violet rays, from 400 down to 300 mμ and infra-red from 750 up to 950m μ can be seen only in radiations of comparatively high power, the visibility in these regions depending greatly on the age of the observer and fluctuating widely for various observers.

We shall confine ourselves to this range of wave-lengths. In the previous chapter we saw that the energy of the solar light which falls each second on each square centimetre of the surface of the Earth's atmosphere equals 0.033 small calories. About 40 per cent of this energy belongs to the visible rays. The opening in the iris of the eye at its largest does not exceed 0.7 sq. cm. It can easily be computed from these figures that the maximum energy of visible solar light that can enter the eye per second does not exceed 0.01 small calories. Of course, if solar light or the light of an electric arc is concentrated by means of a mirror or a lens, this limit can be surpassed by thousands of times. Such mirrors and lenses, however, do not exist in nature, and so facts of this kind could hardly influence the evolution of the eye; hence, they can be left out of our discussion. If the energy of 0.01 small calories per second were concentrated in the region of green rays with a wave-length of 556 mμ (the point of maximum sensitivity of the eye) the eye would get the same visual impression as from a 200,000 candle lamp at a distance of 1m. Such is the upper limit. On the other hand, the eye has to be able to discern very weak light on dark nights, when the intensity is less than a millionth of a candle. The eye has to adapt itself to any intensity throughout this vast range, to be of use to a living creature on Earth.

There are three ways of adapting a photographic camera to changes in brightness. First, the exposure of the snapshot can be varied over a wide range, from thousandths of a second to hours and days. Secondly, the aperture of the objective can be changed by opening or closing the diaphragm. Thirdly, the sensitivity of the plates used varies widely, and different plates may be selected to meet different illuminations.

The first method is inadmissible for the eye, since it always has to take "instantaneous snapshots." The second method is employed by the eye. The opening in the

iris can dilate or contract automatically, depending on the brightness of the light. The largest diameter of the opening is about 8 mm. on the average, and the smallest—about 2 mm. Hence, the area of the opening can vary by about 16 times. Fig. 47 shows how the diameter of the pupil changes as the brightness increases. The logarithms of the brightness are computed along the X-axis, and the diameters of the pupil along the Y-axis.

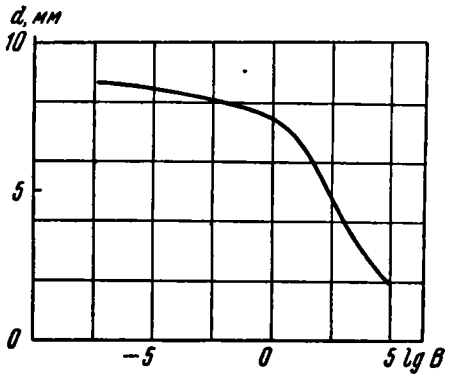


Fig. 47. Change of diameter of the pupil as the illumination increases

Fig. 48 shows how the diameter of the pupil d changes in time after coming from a well-lighted room into darkness. These diagrams make it clear that variation of the diameter of the pupil is absolutely insufficient to compensate for the changes of brightness the eye has to deal with. And so, nature makes use of the third and most radical method, that of varying the sensitivity of the retina. As the eyes adapt themselves to darkness, the sensitivity of the retina increases. In this process the behaviour of the cones is quite different from that of the rods. While the sensitivity of the cones increases by only a few score times compared with their sensitivity in day-

light, that of the rods grows slowly (in the course of an hour and more) in complete darkness, hundreds of thousands of times, reaching a certain limit. The ultimate sensitivity is such that the eye will respond to a visual irritation of 5×10^{-18} small calories per second per sq. cm. by light with a wave-length of 500 mμ. This value, however, differs with different individuals and depends on the conditions of the experiment (small or large light source, intermittent or constant illumination). Besides, to attain such a high sensitivity the image of the source must be produced not in the centre of the retina, but on its periphery, where the sensitivity is greater. This is done by slanting the eye when looking at the light source, i.e., by looking at it "sideways."

A stearine candle 1m. away from the eye sends it about two-ten millionths (2×10^{-7}) of a small calory per second per sq. cm. in the form of visible rays. In order to reduce this quantity to 5×10^{-18} small calories the candle would have to be moved to a distance of 200 km. from the eye. In other words, it may be said that the threshold of optical irritation is equal to the energy of visible light coming every second to each square centimetre of retina from a stearine candle 200 km. away from the eye. It is assumed, of course, that the atmosphere does not absorb light, which is not true to fact.

The astonishing adaptability of the eye to changes in illumination has become especially evident during recent years. From the schematic cross-section of the retina (fig. 44) it can be seen that the outer layer contains black pigment grains. No doubt, the purpose of this pigment is to weaken the light coming through to the rods and cones, and thus to protect them from overbright light. But the protection apparently becomes unnecessary and even a hindrance at night, when illuminations are low. Studies of certain species of animals (fish, amphibia) have shown that under faint light the pigment gradually sinks from the top to the bottom layer

of the retina, and thus no longer hinders the passage of light. The slow migration of the pigment to the bottom of the retina might have been considered to constitute the process of gradual adaption of the eye to darkness; but it has been found that with other animals (e.g., apes) the pigment probably does not migrate at all. This is a problem which still awaits its final solution.

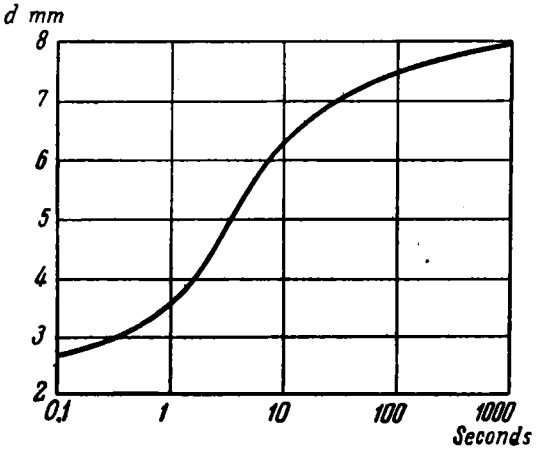


Fig. 48. Change of diameter of the pupil in time after passing from a well-lighted room into the dark

It was stated above that the opening in the iris contracts when the illumination increases, but during certain illnesses, or when certain substances are injected into the organism, the pupil stops contracting and remains wide open irrespective of the illumination. The danger of the eye being blinded on this account is, however, averted. The light rays that fall on the edge of the dilated pupil when the illumination is quite bright cause an optical irritation on the retina about five times as weak as that caused by the ray that passes through the centre of the pupil. How this is achieved is still unknown,

but in any case, it is doubtless that with bright illumination the central part of the pupil does most of the work even if the opening is fully dilated; the light passing through the peripheral parts of the pupil acts on the retina very faintly; on the other hand, when the illumination is weak all parts of the pupil are equally active, so that its wide dilation in the darkness greatly enhances the irritation caused by the light.

It is natural to assume that the black pigment plays an important part in achieving this, by ceasing to shade the retina when the illumination is low. However, pigment migration in the human eye has not been proved as yet.

In the chapter on light we mentioned the general law of light action: light can be absorbed and act only in whole quanta. In other words, it is impossible to make an instrument which would respond to an energy less than one quantum, for the simple reason that light can be discovered only by its action. The energy 5×10^{-18} calories per second (for a wave-length of 500m μ) corresponds to 52 quanta. These 52 quanta are "stretched out" into the space of one second. Hence, it is clear that instantaneously the eye is capable of perceiving a very small number of quanta, i.e. comes close in its properties to an *ideal instrument* as far as sensitivity is concerned.

Making use of this fact, we can observe the interrupted, quantum structure of light with the naked eye. Suppose we are looking at a tiny, faintly luminous spot *A* (fig. 49) the brightness of which can be dimmed arbitrarily. Let us assume that the brightness of the source has been dimmed to such an extent that only a small number of quanta come from it each second to the eye. The quanta cannot follow one another regularly in equal intervals of time; they travel chaotically, sometimes in larger numbers, sometimes in smaller. Of course, bright sources also emit quanta in irregular streams, but

in this case the number of quanta is very great, so that the chance deviations from the mean are practically imperceptible. In the same way, for instance, the percentage fluctuation in the number of new-borns per annum in a large city is very small, and a statistician can forecast it quite accurately; but the number of births per annum in a small house in the same city will fluctuate very widely, so that the statistician's forecast in this case is sure to be false.

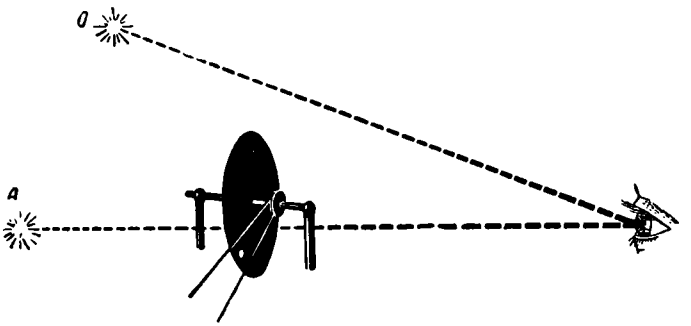


Fig. 49. Diagram of apparatus for observing quantum fluctuations of light

Thus, according to the laws of statistics (if the quantum theory is correct) the brightness of the source should be expected to fluctuate greatly if it is weakened to such an extent that the number of quanta coming to the eye per second is small. If the number of quanta coming to the eye is smaller than that corresponding to the threshold of optical irritation the eye will not perceive any light; on the other hand, if the number of quanta exceeds the threshold value the light will be visible. Hence, if the brightness of the source is gradually diminished there should come a moment after which the source begins to twinkle perceptibly.

The experiment, however, cannot be performed in such a simple manner, for two reasons. First, the eyeball, as

we have mentioned, is very mobile, as a result of which brightness fluctuations are seen with high intensities as well as low. For this reason the eye must be fixed which is done by placing a brighter point *O* (usually red) to one side of the luminous point *A* (see fig. 49). The eye is thus fixed by point *O*, the image of this point being produced in the centre of the retina, while that of the source at *A* is produced on one side, at a constant distance from the centre.

Secondly, the eye possesses the property of retaining visual impressions: this property, for instance, made cinema possible. But this same property is, of course, a hindrance in perceiving the rapid intensity fluctuations of the light source; the fluctuations merge, mix and lose distinctness for the eye.

The difficulty can be overcome in the following manner. A disk with one hole in it (see fig. 49) is placed between the eye and the source. The disk makes one revolution per second, opening the source to the eye only for the period of time it takes the hole to pass (for instance, for one-tenth of a second). With this device the eye sees only short flashes once a second. If the number of quanta during each flash is the same and is greater than the threshold value, there will be a flash each time the hole passes. But if the number of quanta emitted in the time the hole takes to pass is subject to abrupt statistical fluctuations, there will evidently be a visible flash not every time the hole passes before the eye.

This reasoning was fully confirmed by experiment. Indeed, with high intensities the eye sees a flash every time the hole comes by, but when the brightness is gradually weakened, misses begin to occur more and more often as the brightness decreases.

By counting up the number of flashes and misses and applying the laws of statistics the average number of quanta emitted under such conditions for the time of one flash can be determined. Thus, we are able to convince

ourselves of the interrupted, quantum nature of light by "seeing it with our own eyes."

It is worthy of note that in this way we do not determine the sensitivity of the eye as a whole, but only of the cells (rods) ultimately responsible for optical excitation. The sensitivity limits found by different observers up till now vary widely from two to several dozen photon quanta. Separate quanta have literally become visible.

Besides their obvious importance for the theory of light and of the eye, the experiments just described offer the scientist a new method of studying the retina of healthy or unhealthy eyes without surgical operations, and with the eye in its normal state.

We have been discussing the limit values of the energy the eye has to do with on Earth. But the eye can bear direct solar light with difficulty, while brightnesses close to the threshold of optical irritation are perceivable only under great strain. After looking at the Sun for a while, the imprint of its disk on our retina haunts us for quite a length of time: if we look at a white wall we see a dark coloured disk on it—this is the exhausted part of the retina. Similar exhaustion may be caused by ordinary lamps if they are too bright. Sometimes, for instance, after long work with an unshaded electric arc this exhaustion may last for hours, and in the extreme may cause blindness. If we look at the Sun or at a bright light for long, we continue to see the luminous body distinctly after closing our eyes; its colour slowly changes, and its intensity slowly fades (*consecutive images*). Consecutive images, (positive and negative) are a sure sign of abnormal brightness. Sometimes an imprint received under bright illumination remains on the retina all day and all night. It can be seen especially well at night or in the early morning with the eyes closed. In this case the retina acts like a photographic plate. It is still unknown what changes in the retina cause this phenom-

enon. There is apparently a certain brightness, the most pleasant to the eye, which can be observed without strain and borne without fatigue.

Fig. 50 is a graphical representation of the following experiment: the experimentee was required to read an open book at a distance of 25 cm. and to count how many words he could read per minute with various illuminations. The curve was drawn by computing the illumination along the horizontal axis in such a way that the figure 40, for instance, corresponds to a light of 40 candle-power intensity at a distance of one metre from the book; the ordinates are the numbers of words read per minute. The upper curve *a* is that of a normal eye, and the lower one, *b*—of an eye spoiled by long work under artificial light. It can be seen that at first the reading efficiency grows rapidly with the illumination, but at 100 luxes* the growth ceases. This is a very important fact which must be taken into account when illuminating shops, rooms, etc.

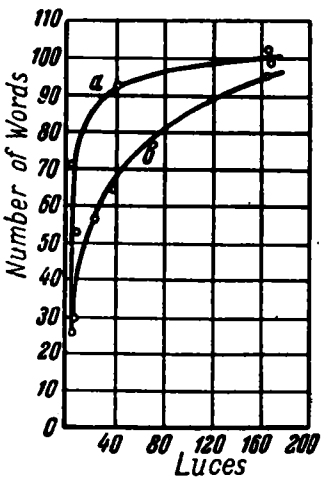


Fig. 50. Rapidity of reading depending on the illumination

Numerous experiments carried out by lighting engineers and physicians during the past decade have shown that the efficiency of various kinds of work increases tangibly if the illumination is raised to 300 and

* Lux—the illumination produced by one candle at a distance of one metre.

even to 500 luxes, without the eye getting perceptibly fatigued. This is the limit towards which our lighting engineering should tend. In most cases we are still far from it. Artificial lighting has not as yet drawn the attention it deserves.

The illumination of the natural environment and the brightness of the images on the retina of the eye vary widely depending on the season and the time of day, on the cloudiness, on the objects around us (verdure, snow). It is impossible to deduce a mean "optimum" for all living creatures. It is different for diurnal than for nocturnal animals (owls, bats). To the latter the light of our weakest lamps and candles is unbearable. From a biological standpoint the "optimum illumination" should be a result of the evolutional adaption of the eye to the mean illumination produced on Earth by the Sun. *The eye is adapted not to the energy of the Sun, but to that of the solar light dispersed by the surrounding bodies.* This is borne out by the variable diaphragm of the pupil, by the variable sensitivity of the retina and by the existence of an optimum brightness.

It should be noted that it is not so much the total energy entering the eye that fatigues the retina, as the energy per unit area of the image on the retina. The farther off a candle is, the smaller its image; but the "specific brightness," i.e., the brightness per unit area of the image remains constant over a wide range of distances. Looking down a long row of lighted street-lamps in a city street, we find that the brightness of all of them appears almost the same irrespective of the distance (the light of the far lamps is weakened a little due to absorption by the dusty air). It is another thing if we illuminate some surface with the light from the first, second, third, etc. lamp; in this case we shall find that the illumination diminishes very rapidly as the distance from the lamp increases. A dim light will fatigue the eye badly if stared at, because the image of the

filament on the retina is of high "specific brightness." For this reason, lamps are usually fitted with light-dispersing hoods and shades. Forgetfulness of this fact is the reason for the frequent complaints that modern luminescent lamps made in the shape of narrow luminous tubes cause "eye-ache." This can easily be eliminated by shading banks of several such lamps each with light-dispersing plates of frosted or opal glass. Otherwise, the lamps may be concealed so that they give light, but are themselves not visible. Of course, the simplest way is to avoid looking directly at the lamp, by keeping the eyes on the objects it illuminates.

Up till now we have been dealing only with the absolute estimation of luminous energy by the eye. This estimation is entirely qualitative: great brightnesses "hurt," very low brightnesses make us "strain our eyes," and there are brightnesses which are "convenient and pleasant" to us; but we feel neither the change in the size of the pupil, nor in the sensitivity of the retina; only these processes could give us a real estimate of brightness, but they do not reach our consciousness. We notice distinctly only the minimum magnitude of light (the threshold of irritation), because it is followed by a complete obliteration of visual impression. For this reason only the existence of the threshold of optical sensation enables us sometimes to use the eye as an instrument for absolute measurements of luminous energy.

But the eye is capable of *comparing* brightnesses, of distinguishing brighter surfaces from darker ones. Such comparisons are in themselves also qualitative, but they can easily be employed for quantitative measurements. Suppose each of two adjacent white surfaces is illuminated by a sepnate lamp (fig. 51). One of the surfaces seems brighter, the other darker. There are many methods of reducing the intensity of light a known number of times (the simplest being to move the lamp away).

Now let us change the distance between one of the lamps and the surface it illuminates, until the brightnesses of the adjacent surfaces become equal. When this has been done it may be said that one lamp is as many times more powerful than the other as its light had to be weakened to give equal illumination. If, for instance, a candle were placed at the right, and a 16 candle-power lamp at the left, the latter would have to be weakened sixteenfold (for instance, by moving it away to four times the distance between the candle and its surface) to attain equal illumination. This method is called photometrical measurement, and the apparatuses for these measurements—*photometers*.

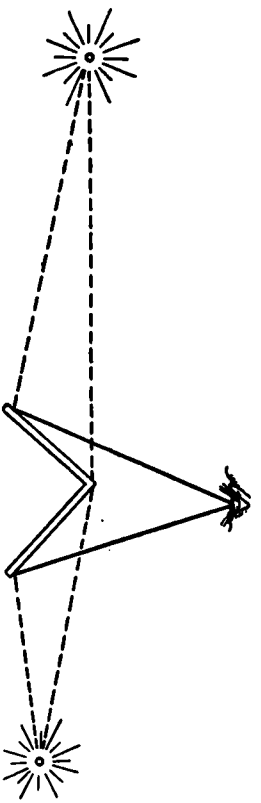


Fig. 51. Diagram of photometer

There are at present a great many different types of photometers based on the photographic, photochemical and photoelectrical action of light. These instruments can be used for measurements not only of visible, but also of infra-red and ultra-violet light, and are very accurate. Just now, however, the photometer is interesting to us inasmuch as it enables us to disclose some very important properties of the human eye.

What is the accuracy of the eye in judging whether the illumination of two surfaces is equal or not? What difference of illumination can it notice? For instance,

almost symmetrically on both sides. Ultra-violet rays with long waves (about 360mμ) are visible if their intensity is high. Their colour is violet. Rays of shorter wave-lengths, down to about 300 mμ can also be seen, though dimly. Such waves are largely absorbed by the crystalline lens of the eye, and only a very small fraction of them reaches the retina. But, being absorbed, they cause a blue fluorescence in the eye, which the

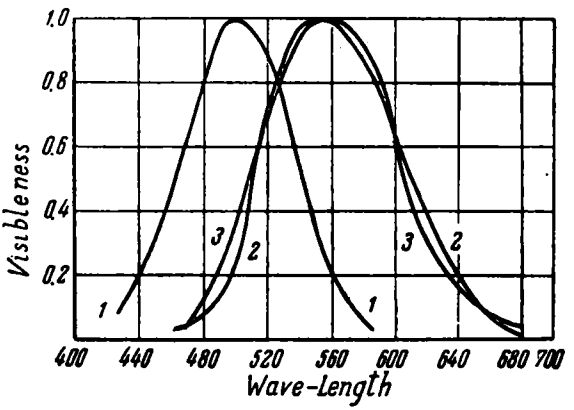


Fig. 52. "Daylight" and "twilight" visibility curves

retina also sees. For instance, if a powerful source of ultra-violet rays—a mercury quartz lamp—is looked at through a special black glass which stops all the visible rays and transmits only the ultra-violet, the room seems filled with a bluish haze, resembling tobacco smoke. This "smoke" is the fluorescence of the eye seen by the retina.

Normal eyes see only a small region of the boundless range of rays. What is it that determines the range of visibility? Remember (see previous chapter) that the solar spectrum for the Earth's surface ends, practically, at about 290 mμ, the shorter waves being stopped by

the ozone layer of the atmosphere. Biologically the existence of an eye adapted to perception of rays with waves shorter than 290 mμ would, of course, be purposeless. But there is another reason, which not only keeps the eye from adapting itself to the perception of ultra-violet rays, but even makes it protect itself against them. Short-wave rays in most cases chemically decompose organic substances and may kill live organisms. This is what the action of the so-called germicide mercury lamps is based on. These lamps are made of quartz, or, more often, of a special kind of glass which is transparent to short ultra-violet waves, and the light they give is used to disinfect hospital rooms, storehouses for foodstuffs, municipal water supplies, etc. This light also produces artificial sun-tan, but may blind the eye if the latter is exposed to ultra-violet rays with a wave-length of about 250 mμ for a long period of time.

The retina of the human eye, as we have shown, is quite sensitive to rays with wave-lengths below 400 mμ (the practical limit of the visible spectrum), but these rays are hardly let through to the retina at all, owing to the fact that the crystalline lens of the eye absorbs them greatly. The lens not only produces the image on the retina, but serves as a light filter as well, protecting it from rays with wave-lengths of about 400mμ and less. By perceptibly stopping the blue and violet rays, the lens helps to reduce chromatic aberration in the eye, thus making the image more distinct.

The reasons stated above fully explain, biologically, why the lower limit of visible light is at about 400mμ.

Let us turn to the upper limit of visibility. Why does the eye stop seeing in the region of infra-red rays? In this connection also, two very sound reasons can be given. Suppose the eye were sensitive to infra-red rays, just as it is to green rays. In such a case something difficult for human beings to imagine would happen. All

suppose we have before us two surfaces, equally illuminated by one-thousand-candle-power lamps at a distance of 1m. from each; would we notice the difference if one candle were added to one of the sides? Experiment shows that we would not, that about twenty candles would have to be added for the difference to become perceptible. Hence, the ratio of the least perceptible increment of illumination to the initial illumination is 20:1000, or 2 per cent. The corresponding percentage increments for various intensities (in candles) of yellow light with a wave-length of 605 mμ are given in Table 2.

Table 2

Candle-power	Least perceptible increment per cent	Candle-power	Least perceptible increment per cent
200,000	4.25	100	2.78
50,000	2.55	50	3.78
20,000	1.83	20	4.60
10,000	1.63	10	6.10
5,000	1.58	5	10.3
2,000	1.80	2	16.7
1,000	1.98	1	21.2
500	2.25	0.5	27.6
200	2.35	0.2	33.2

The highest intensity in the table of 200,000 candle-power approximately equals the illumination of direct solar light. The table shows that the eye discerns differences of brightness best of all with intensities of about 5,000 candle-power; with greater and smaller brightnesses this faculty weakens and the least perceptible percentage increment increases, although it is almost

constant (about 2 per cent) between 200 and 20,000 candle-power.

The faculty of distinguishing brightnesses is, of course, of great importance for living creatures; it enables them to distinguish objects from one another. The interval in which this faculty is the most active (200-20,000 candles) corresponds approximately to the above-mentioned range of illuminations caused by the Sun. Consequently, the faculty of distinguishing brightnesses, like the absolute perception of brightnesses by the eye, is adapted to the Sun: not to direct solar light, however, but to solar rays dispersed by the atmosphere and the objects around us.

The "sunniness" of the eye, or, more accurately, its adaption to solar light, manifests itself best of all in its response to the spectral composition of light. The scale of wave-lengths is boundless: the long-wave end extends into infinity, while the shortest waves are infinitesimal. The region of visible waves is lost in this diversity. Suppose rays of various wave-lengths but of equal energy were to fall upon the eye. The infra-red rays would not be visible at all, the red would be discernible, but rather weak, the yellow-green rays would seem the brightest of all, the violet hardly perceptible, and the ultra-violet almost altogether invisible.

If we accept the brightness of the yellow-green rays as unity and compare the brightness of all the other rays with it, the energy being equal in all cases (practically this is rather difficult to do), we obtain the so-called "visibleness" curve of the rays, shown in fig. 52. In this figure the wave-lengths are computed along the horizontal axis, and the visibleness along the vertical axis. With considerable brightnesses the curves at the right are obtained; curve *2* is that of the "average" eye, and curve *3*—that of an individual chance observer. It can be seen that the maximum is in the yellow-green region (556m μ), and that the curve drops abruptly and

heated bodies, as we have seen, radiate light; the radiations of bodies that are not strongly heated are concentrated wholly in the infra-red region of the spectrum. The temperature of the human body, including the cavity of the eye, is about 37°C. According to the laws of heat radiation it can be calculated (see p. 62) that the radiation maximum of the human body corresponds to the region of 9-10 μ, and that the energy radiated per square centimetre each second equals 0.012 calories. Of course, the inner walls of the eye also radiate this energy; the inside of the eye emits infra-red light, while the surface inside the cavity of the eye absorbs as much as it radiates. The total inner surface of the eye is about 17 sq. cm. Multiplying 0.012 by 17 we get 0.2 calories, as the total energy of the eye's intrinsic invisible light, absorbed by itself. Now suppose for a moment that this invisible infra-red light became visible, like green light. One "green candle" at a distance of one metre emits 38-thousand millionths of a calory per second per square centimetre; 0.2 calories are equivalent to 5 million candles. The inside of the eye would begin to glow with an intensity of millions of candle-power. This intrinsic light would outshine the Sun and all the surroundings. Man would see only the inside of his own eye and nothing else, which is the same as being blind.

For this reason it is quite appropriate that the eye does not see long-wave infra-red rays.

But why are infra-red rays of shorter wave-lengths, say, from 1 to 5 μ, not visible either? Apparently the reason for this lies in the very mechanism of vision. This mechanism is not known to this day, but it may be affirmed that vision should begin either where the chemical or photoelectrical effect of light begins (the latter consists in the tearing away of electrons from molecules). However, photochemical or photoelectrical processes can occur only if the energy is not less than a certain mini-

mum, otherwise the molecule cannot be torn apart, nor an electron torn away from it.

There are several photoelectrical processes known at present which extend very far into the infra-red region as regards possible sensitivity, up to 5-6 μ (viz., increase of electrical conductivity under the action of light). But the sensitivity in these cases is very low. Photographic plates are also insensitive to this range of wave-lengths.

All these reasons, some of which depend on the properties of solar light, and others—on the peculiarities of light action on substances, explain quite adequately why the eye can see only in the narrow region of the spectrum, approximately between 0.4 and 0.7 μ.

But there is still another solar factor which determines this "natural selection" of the region of visibility. Let us consider the distribution of energy in the solar spectrum. This distribution is by no means constant for a creature living on the Earth's surface. It varies greatly depending on the position of the Sun in the sky. At different heights above the horizon the rays of the Sun have to penetrate different thicknesses of atmosphere, which disperse and absorb rays of different wave-lengths differently. This has already been mentioned in the chapter on the Sun. Fig. 53 shows smoothed-out energy distribution curves without Fraunhofer lines for solar light: *I*—outside of the atmosphere: *II*—with the Sun overhead; *III*—with the Sun 30° above the horizon; *IV*—under conditions approximating those at sunrise and sunset, 10° above the horizon. The upper curve in fig. 54 is the mean annual energy distribution curve for the midday Sun. The latter mean curve is, of course, the most important for the eye.

From this curve it follows that with the "average" Sun the energy is distributed almost uniformly throughout the region between 450 and 650mμ, but drops sharply outside of these limits. In other words, the visibility curve enclosing the shaded area *I* in fig. 54 is

situated within the most advantageous part of the distribution curve of mean solar light*.

If the eye's only task were to perceive luminous energy as economically as possible, the best solution of the problem would be, of course, uniform sensitivity throughout the whole interval between 0.4 and 0.7 μ.

But that would be a rough and simplified approach to the problem. Biologically the essential thing is not

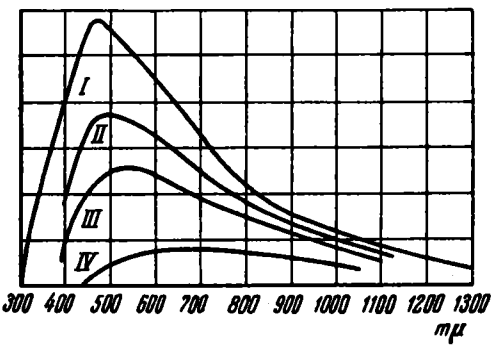


Fig. 53. Distribution of energy in the solar spectrum with the Sun at various heights above the horizon

the absolute sensitivity of the eye to these or those light waves, but the capability of best *distinguishing* objects from one another. Biologically, to see does not mean just to receive a visual sensation, but to be able to discern the details of the surroundings. The narrowness and abruptness of the visibility curve considerably weakens the influence of chromatic aberration, making

* The spectral sensitivity of the eye coincides with the maximum of the solar energy distribution curve if the spectral curves are expressed in a wave-length scale, and does not if they are drawn to a frequency scale. Hence, the adaption of the eye to the Sun is determined not by this coincidence, but by the aggregate of factors discussed in S. I. Vavilov's book.—*Ed.*

the image on the retina more distinct. The same end is attained by light waves of different lengths being reflected differently by different objects. It is very important, moreover, that the *sharpness of contrast* of the various objects around us in colour and brightness is greatly enhanced due to the visibility curve of the eye *having a sharp maximum* and not sloping but falling steeply towards both ends of the spectrum. This is precisely what separates the surrounding objects so distinctly from one another for the eye.

Let us return to what we discussed in the chapter on light—to Newton's interference rings. If we were to measure the energy reflected from the flat glass and the lens by means of an instrument equally sensitive to all wave-lengths (a thermoelement is just such an instrument) we should not notice the Newtonian rings at all.* The eye can discern these rings clearly only because its visibility curve is narrow and has a sharp maximum. If the eye's sensitivity curve were a wide one very many things around us would be indiscernible.

It should be noted that the visibility curve for daylight vision almost coincides with the mean energy distribution curve of solar light reflected and dispersed by green plants. This circumstance is, of course, a very happy one for creatures that live among plants and feed largely on them.

Thus, we have an example of the successful adaptation of the eye to the real conditions of life on Earth, and a proof of the genuine kinship between the eye and the Sun.

With very feeble illuminations the visibility curve changes radically. The left curves in figs. 52 and 54 are

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* This concerns observation in white light, when the maxima of the waves of some lengths coincide with the minima of others; the eye's highly selective ability to distinguish colours helps in this case also to discern separate maxima, although energy maxima and minima may not exist.—*Ed.*

the visibility curves for dim illuminations: it can be seen that they have shifted considerably into the blue region of the spectrum, compared with the curve for bright illuminations. Physiologists explain this peculiarity of twilight (scotoptic) vision as follows. The retina, as we have seen, has two kinds of light-sensitive elements—cones and rods. In daylight (photoptic) vision the work is done mainly by the cones, but they are not very sensitive, and cease functioning when the light becomes faint. Then the rods, which have a different visibility curve, come into play. From this standpoint curve *I* in fig. 54 corresponds to the "day" cones, and curve *II*—to the "night" rods.

If the day visibility curve results from the adaption of the eye to solar light dispersed by the atmosphere, verdure, etc., then, it would seem that the "night" curve should be adapted to the night sky. The luminosity of the night sky (when there is no Moon dispersing direct solar light) consists of the light of the stars, of an infinitesimal dispersion of the Sun's rays, which penetrate into the atmosphere slightly even late at night, and of the luminosity of the sky proper, which constitutes a considerable part of the total light emitted. The sky's own luminosity is due to the emission of light by oxygen and nitrogen atoms in the upper layers of the atmosphere. The spectrum of the night luminosity of the sky is linear with an especially bright green line having a wavelength of 558 mμ. The luminosity of the sky reaches its maximum about midnight. However, as to the question of the adaption of the "night" visibility curve to the night sky, a number of difficulties have not been overcome to this day. The number of measurements of the total distribution of the luminous energy coming from the stars and that coming from the sky proper is still insufficient. According to the experiments of P. P. Feofilov, performed in the winter of 1941, the total energy distribution of the night sky is equivalent to that of a black

radiator with a temperature of 4,000°, i.e., is red, and not blue, as was expected. These measurements cannot, however, be considered universal; they have to be

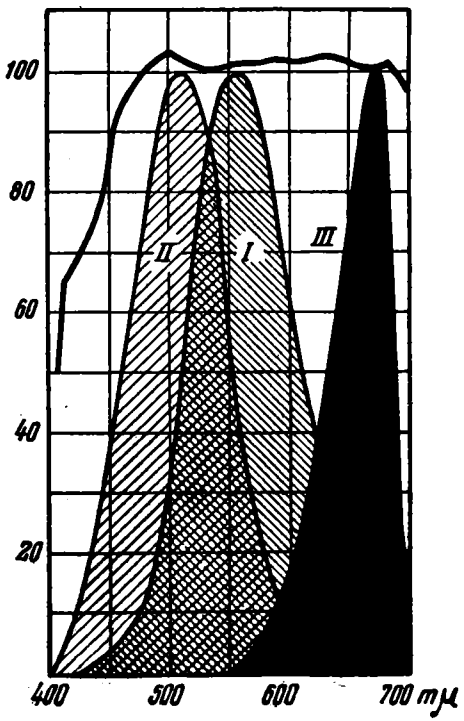

Fig. 54. Mean annual energy distribution curve for the midday Sun at middle latitudes (upper curve)
I—Daylight visibility curve
II—Twilight visibility curve
III—Chlorophyl absorption curve

repeated and extended at various points of the globe and in various seasons of the year. Besides, it must again be emphasized that the main thing for the eye is not the

visual sensation in itself, but the possibility of distinguishing the surrounding objects from one another, this being even more important under the difficult conditions of night than during the day. These questions have been studied very little as yet. It cannot be considered that the shifting of the night visibility curve towards the short-wave end of the spectrum is purely a matter of chance. The entire history of development of living beings leads us to assume that the shifting of the night visibility curve tends to increase the distinguishing capacity of the eye at night.

Unlike the eye, whose business it is to see, the leaf of a plant has to assimilate luminous energy for chemical changes. This fact finds expression in the spectral location of the photochemical sensitivity curve of green plants. Area *III* in fig. 54 represents the main absorption curve of chlorophyll, the green colouring matter in plants. In comparison to the day visibility curve, the maximum of the absorption curve is shifted sharply in the direction of the longer waves. How rational is this from a biological standpoint? Why are the long waves more advantageous in this case?

Let us return to the fundamental law of photochemistry which we discussed in the chapter on light (p.37). We saw that to bring about chemical change in a molecule one quantum $h\nu$ had to be absorbed. Of course, the energy of this quantum must exceed a certain minimum value $h\nu_0$, necessary for the chemical decomposition, otherwise the reaction will not take place. Hence, it is clear that the probability of chemical processes taking place under the action of infra-red rays is very low.

On the other hand, the chemical change can take place under the action of any of the quanta $h\nu$ absorbed, provided their energy is greater than $h\nu_0$. But no matter how great the energy of the quantum, it can be absorbed by only one molecule and will cause the same

effect as a quantum of low energy, if only this energy is greater than $h\nu_0$. Thus, from a photochemical standpoint the most advantageous quanta for the plant are those with the least energy (greater, however, than $h\nu_0$), i.e., with the largest permissible wave-length.

If we now take into account the mean distribution curve of solar light, shown in fig. 54 (upper graph) it becomes evident that the most advantageous part of the uniform section between 450 and 650m μ to place the chlorophyll curve in is the 600-700m μ zone, where it actually is situated.

When the photographer has to shift the maximum of the spectral sensitivity of a plate from one region to another, he colours the sensitive layer with various organic pigments called "sensitizers," thus obtaining photographic layers especially sensitive to red, yellow or green rays, according to his needs. Exactly the same, as we have seen, happens in nature, the visual purple and the chlorophyll acting as sensitizers.

The shape of the visibility curve is of great importance in lighting engineering. Most artificial light sources utilize the radiations caused by heating (candles, kerosene lamps, incandescent lamps, etc.); only part of the rays in these radiations is visible, the rest being lost irrevocably for the eye. As the temperature of a black body is increased, larger and larger portions of the radiant energy shift from the infra-red into the visible region, and the light source becomes more efficient. However, this does not continue indefinitely. As the temperature rises, part of the radiant energy also passes into the invisible ultra-violet zone. It is theoretically possible to reach such temperatures where an immense part of the radiant energy has shifted into the invisible region of ultra-violet and X-rays. Consequently, there must be a certain temperature of incandescence of light sources which is the most advantageous for the eye. What is the magnitude of this temperature?

Table 3 shows the percentage of radiant energy emitted as visible light at various temperatures.

Table 3

Abs. temperature, °K. . .	1500	2000	3000	4000	6000	8000	12000
Energy emitted as visible light, per cent	0.0	1.7	14.6	31.8	49.7	47.7	18.6

It can be seen that the most advantageous temperature is 6000°, at which half the energy radiated turns into visible light. But this is the temperature of the Sun! What is the connection between the radiations of the Sun, a black body and the eye? Is this coincidence we have found mere chance? After all we have learned about light, the Sun and the eye, after we have convinced ourselves that the eye developed as a result of the existence of the Sun, in a certain sense for the Sun and under the influence of the Sun, this connection seems quite natural and necessary. Both the Sun and the luminous black body are observed by the same eye. But the eye is adapted to the Sun, and that is why similarity of the spectrum of the artificial source to the solar spectrum is the best solution of the problem.

How good is the eye at making out the spectral composition of light? Up till now we have convinced ourselves only of the fact that the eye does not sense most of the spectral regions at all, while in the visible zone some rays seem brighter to the eye, others fainter. If we make the brightness of red and blue light approximately the same, we know that nevertheless the eye will distinguish the rays from one another unerringly. Hence, the eye has other possibilities besides the magnitude of the sensation, for making out the spectral composition of light. The eye distinguishes seven rainbow colours in

the solar spectrum, and a large number of tints which varies with different observers reaching several hundred in some cases. The capacity of the eye to distinguish colours can be expressed as follows. Two neighbouring sections of a continuous spectrum are compared, and it is found by how many millimicrons one of these sections can be changed without the eye noticing the difference in colour. This greatest difference of wave-lengths in millimicrons can characterize the capacity of distinguishing colours in the given part of the spectrum. Fig. 55 shows the curve of the distinguishing capacity of the eye obtained in this manner. The abscissae are the wave-lengths and the ordinates—the greatest permissible dif-

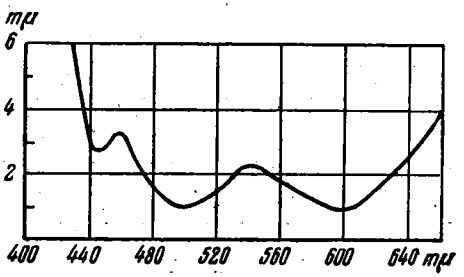

Fig. 55. Graph of spectral distinguishing capacity of the eye

ference of wave-lengths with which the eye does not notice any difference in colour. The curve is very complex in shape. Still, it gives some grounds for our subjective division of the spectrum into the rainbow colours. All the minima and maxima of this curve may be regarded as kinds of boundary marks between the rainbow colours. Thus, the boundary between the violet and indigo is approximately at 445mμ, between the indigo and blue—at 460mμ, between the blue and green—at 500 mμ, between the green and yellow—at 540m μ, and between the yellow and orange—at 600 m μ. Further measurements in the red region have not been made as yet.

Only the cones possess the capacity to distinguish colours; in twilight vision, when the rods come into action, the colours of the spectrum disappear and everything seems grey. The absence of cones in the retina of the eyes of owls, bats and fish lead to the conclusion that these creatures are devoid of colour vision. The world looks like a black-and-white photograph to them. The human eye has two different light-sensitive apparatuses. One of them may be likened to a camera taking colour photographs, is not very sensitive and is for use during the day; the other, used in twilight or at night, "takes" ordinary black-and-white photographs, but is very sensitive.

However, the capacity of the eye to distinguish colours cannot compete with spectral analysis. If we resolve light spatially into its simple rays the eye can distinguish one ray from another quite distinctly by the difference in hue. But the eye can easily be deceived. Any pure spectral colour can be produced by mixing three other simple colours, e.g., red, green and violet, in various proportions. This is what the simplest methods of colour photography and cinema are based on.

Three ordinary snapshots are taken of the coloured object through red, green and violet-coloured glasses (light filters) respectively. All three negatives look like ordinary ones; they are used to produce photographic prints on glass (lantern slides). The difference in these slides is that one of them was formed predominantly by red rays, the second by green and the third, by violet rays; that is why the lights and darks in the snapshots are different. The lantern slides are dyed the same colour as the filters they were taken through. If now the light beams of three projection lanterns are focused on the same spot of a screen and the coloured slides placed in these lanterns, the red, green and violet images will coincide and produce the photographed object on the screen in all its natural colours. The three colours will

produce all the rest. For instance, if a certain part of the object was white, the rays from this part will have entered the camera through all three filters. Consequently, when the colours are combined the red, green and violet will be superposed in this part of the screen, and together will give the eye the sensation of white. If part of the object was yellow, the rays from here will have passed through the red and green glasses, but not through the blue one; there will be a black spot in the corresponding part of the blue slide, which will not transmit light. As a result, only the red and green colours will be projected on to the screen, giving the eye the impression of yellow, and so on. The technique of modern colour photography is much more complicated than that described. But in all the so-called "additive" methods the principle is essentially the same.*

Generally speaking, any colour of the spectrum can be produced by blending three simple colours in various proportions. But the same three colours, when mixed, can produce colours which do not exist in the spectrum, such as white or purple. If white is added to a simple colour, for instance, red, the colour remains red, but it becomes more and more dilute; its saturation decreases. Consequently, an infinite variety of reds can be produced from the simple red alone, ranging in saturation from

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* Colour photography gives an impression which is true only for the "daylight" eye. In dim light, for instance, in the moonlight, the colours of objects become essentially different to us, because the vision curve has shifted towards the short-wave end of the spectrum and because colour perception disappears in twilight vision. For instance, the Moon seems to emit a greenish light, in spite of the fact that the energy distribution in the moonlight spectrum is almost the same as in that of sunlight. If we were to take a colour photograph by ordinary methods of a landscape illuminated by the Moon, using a camera with a high aperture ratio, we should probably get an ordinary picture with the usual day colouring, entirely different from the actual picture that presents itself to the eye.

pure red to pure white. In general, three features characterize any colour for the eye: *brightness, hue* and *saturation.* Thus, the variety of colours discernible by man is infinitely greater than that in the visible spectrum. From this standpoint the eye is a *very poor instrument* for the spectral analysis of light.

In warfare, guns, trenches, etc., are painted the colour of the ground, the grass, etc., to camouflage them from the eyes of the enemy. In spite of the fact that the light coming from the camouflaged object differs considerably in spectral composition from that of the background, the eye is easily deceived, and only a spectroscope is able to disclose the delusion. In the animal world camouflage, adaption of the creature to the colour of its surroundings, is exceedingly wide-spread; many insects are of the same green colour as leaves and grass, hares change their fur, adapting themselves in winter to the white snow, and in summer to the brownish colour of the ground, etc. It is noteworthy that very often the colour of the camouflaged animal is the same as that of the environment not only visually, i.e., to the eye, but coincides with it in spectral composition as well. This perfect protection makes us suspect that maybe the quality of the eyes of some animals, the enemies of those camouflaged from their vision, is somewhat higher than that of the human eye.

The imperfection of the eye as a spectroscope is quite comprehensible. The physicist is able to resolve complex light into simple light only by separating its constituent simple rays *spatially,* using prisms and other instruments for the purpose.* The spectral composition can be

* The simplest type of spectroscope could be made as follows. Paint a rainbow spectrum on white paper with colours that disperse only a very narrow range of wave-lengths and absorb all the rest. It should be noted that such colours are very difficult to prepare. If the rainbow band painted in this way is illuminated, for instance, with light from a mercury lamp, a rough image of the

appraised but roughly without spatial separation of the rays by the action on substance peculiar to the individual zones of the spectrum. For instance, red rays act feebly on photographic plates, while the action of blue rays is much stronger. It is really astonishing how each simple colour causes its own peculiar reaction in the eye independent of the energy, though the rays are not separated spatially at all. In our artificial instruments the action of rays of one kind can always be imitated by the action of others, by adjusting the energy, provided the spectrum is a continuous one. So far, we do not know for certain how this high degree of perfection is attained in the retina of the eye. It is assumed that there are three different kinds of light-sensitive elements in the retina, each having its own special wide range of stimulation (fig. 56). If, for instance, red light falls on the eye, all three elements are involved, since they all absorb red, though to different degrees. The eye feels this *difference*, which is accompanied by the sensation of red. Green also stimulates all three elements, but in different proportions than red, etc. The sensation of the total stimulation in all three elements corresponds to the brightness of the incident light, while the relative stimulation in the three different elements gives the sensation of hue. If there were only one element left, *relative* stimulation would be out of the question, and there would be no sensation of hue, although the impression of brightness would remain as before. This conception very well explains the possibility

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mercury spectrum will be seen on the paper. The yellow mercury line will be dispersed only by the yellow zone of the painted band, the green line by the green zone, the blue by the blue zone, etc. The mercury light will be resolved into its spectrum. A spectroscope of this kind can, of course, give only rough results, but its advantage is that it requires no slits or prisms. Of course, the painted spectrum may be substituted by an assortment of narrow transparent coloured films, together making up the spectrum. Light from any source passed through such a spectral assortment of films on to a screen will produce a rough spectrum.

of producing any colour by combining three others, cases of colour-blindness (Daltonism, etc.), when the eye loses the sensation of hue in certain parts of the spectrum, etc. But so far this theory has not found irreproachable confirmation in anatomy.

The sensation of colour greatly increases the value of visual perception. Colour vision enables us to distinguish objects very rapidly and in an original way. Suppose there were no colour perception, and that we had to distinguish objects from one another as we do on

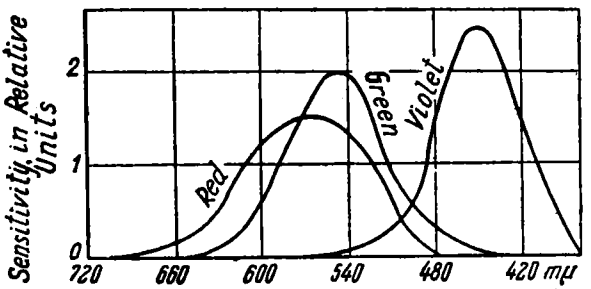

Fig. 56. Graph of the three "basic stimulations"

ordinary photographs, only by the quantity of light dispersed. In such a case any two photometrically equal surfaces would become indistinguishable even though they were of different colours, say, yellow and green, and the picture of the world around us would immediately become much poorer in detail. Besides, differences in colour are perceived immediately, while it takes a long time and even requires quantitative measurements to establish small differences in brightness (the more so if the objects compared are far away from one another). This is to say nothing of the purely aesthetic element of colour perception.

In view of these great advantages of colour perception, it has been found very useful to carry colourity into

realms from which it seems to be eliminated by its very essence, e.g. in studying objects illuminated by invisible ultra-violet or infra-red rays. Nevertheless, this is quite possible, as has been shown in microscopy by E. M. Brumberg.

Suppose we have to take a photomicrograph of a certain preparation in ultra-violet light. We take three pictures with three wave-lengths, being careful to make them all to the same scale. The photographs produced in the three ultra-violet wave-lengths will generally be different, since various wave-lengths are absorbed differently. Now we do the same with these three "black" photographs as in colour photography (p. 130). We project them through differently coloured glasses, say, red, green and violet, on to a common screen, making the images coincide. In this way, we get a coloured snapshot of an object photographed in invisible light. In this case, of course, the photograph is artificial. Various coloured glasses may be used, to obtain various colour photographs. Such artificial colour snapshots of objects photographed in invisible light offer many practical advantages, making it possible quickly to discover details in the object, which would have been otherwise unnoticed, and to perform qualitative chemical analyses.

Of course, this method can be carried from the realm of microscopy into all branches using photography in invisible light. In employing it the experimenter copies nature in which this wonderful method of visual perception already exists.

Our rather confused excursion through various branches of knowledge has come to an end. Mainly with the help of physics, astronomy and biology we have finally come to an understanding of the true nature of the indubitable kinship between the eye and the Sun.

This connection is almost the same as that between a photographic camera and the source of the light the picture is taken in. Of course, in most cases it is not

the light source that is photographed, but an object illuminated by it. The object, however, can be photographed only because it disperses the rays coming from the source, and therefore, the camera must be adapted to these rays. Its objective must transmit them, producing a correct image; the photographic plate must be of high enough sensitivity in the right region of the spectrum; the camera must have a diaphragm to make it adaptable to various conditions of lighting. Plates of different sensitivity must be used, depending on the illumination. All these properties can be found in the eye, which has adapted itself to the Sun as a light source. The crystalline lens of the eye transmits to the retina only those of the Sun's rays which are not harmful to the organism, and produces a good image in the solar wavelengths. The retina of the eye is very sensitive, but for daylight conditions this sensitivity is greatly reduced, being increased again at night. The eye has a diaphragm which changes automatically over a wide range (depending on the illumination). The spectral sensitivity of the eye falls on the maximum of the spectral energy curve of the Sun.*

All this is a result of the adaption of the eye to the solar light on the Earth.

The eye cannot be understood if we do not know about the Sun. On the other hand, the properties of the Sun can serve as a basis to outline the peculiarities of the eye theoretically, without knowing them beforehand.

This is why the eye is "like unto the Sun," as the poet puts it.

* See footnote, p. 122.—*Ed.*